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Environmental Effects of Utilizing Solid Waste as a Supplementary Power Plant Fuel

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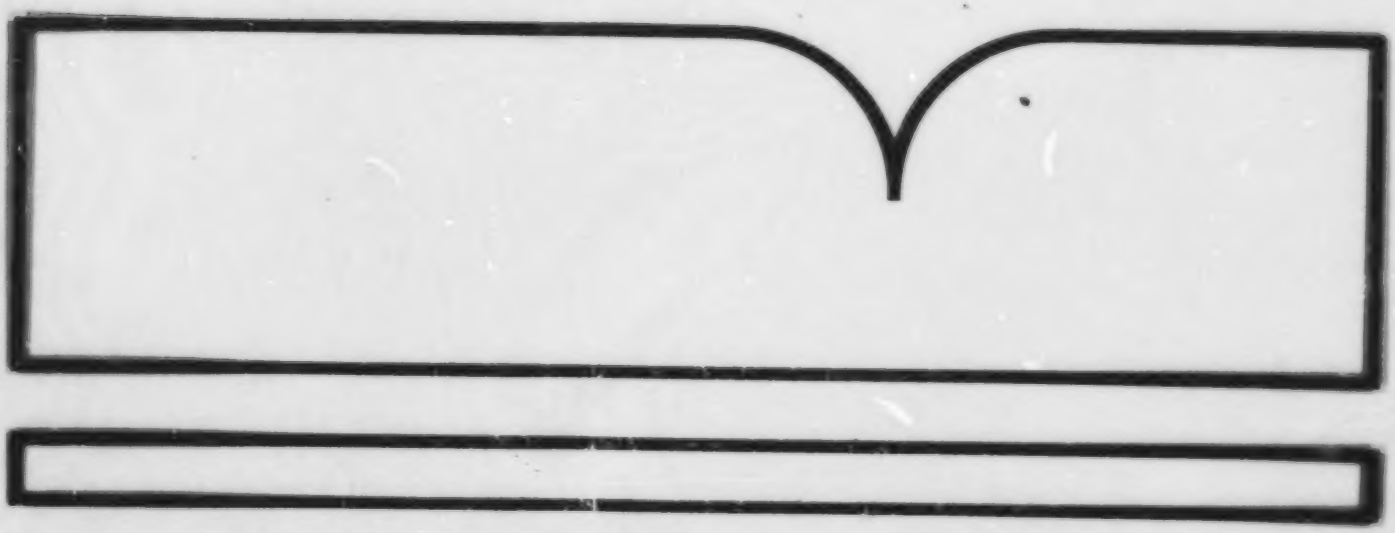

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ENVIRONMENTAL EFFECTS OF UTILIZING SOLID WASTE AS A SUPPLEMENTARY POWER PLANT FUEL

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16. ABSTRACT

The results of 3 years of research on the utilization of shredded and magnetically separated municipal refuse to supplement high-sulfur coal as fuel in a stoker-fired boiler are presented. During the first half of the research, a refuse handling and furnace feed system consisting of agriculture crop handling equipment was used. With this equipment the feasibility of blowing shredded refuse into a boiler and burning it completely on a traveling grate was demonstrated. Corrosion probe exposures were used to show the effectiveness of cofiring to reduce short-term corrosion of boiler tube metals. Reduced emissions of SO_2 from the high-sulfur coal also resulted from dilution of the coal with refuse and by action of alkaline components of the refuse.

It was demonstrated that 700-hour corrosion rates with an average of 22 weight percent refuse and high-sulfur coal were 5 to 10 times less than those with bulk refuse burning and about equal to those from coal alone. Sulfur dioxide emissions were reduced as a function of the refuse content of the mixture. The cofiring with refuse had no significant effect on particulate loading of the flue gases, fly ash resistivity, or grate ash composition, but the ash fusion temperature was lowered somewhat.

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FOREWORD

When energy and material resources are extracted, processed, converted, and used, the related impacts on our environment, and even on our health, often require that new and increasingly more efficient pollution control methods be used. The Industrial Environmental Research Laboratory-Cincinnati (IERL-Ci) assists in developing and demonstrating new and improved methodologies that will meet these needs both efficiently and economically.

The subject of this report is an evaluation of the effects of combusting solid waste with coal in a grate-fired utility boiler. The information contained herein will be of interest to those involved in the purchase, design, construction, or operation of waste-to-energy systems. Inquiries and comments regarding this report should be directed to the Industrial Waste Combustion Group, Energy Pollution Control Division.

David G. Stephan
Director
Industrial Environmental Research Laboratory
Cincinnati

ABSTRACT

The results of 3 years of research on the utilization of shredded and magnetically separated municipal refuse to supplement high-sulfur coal as fuel in a stoker-fired boiler are presented. The facilities of the Columbus, Ohio, Municipal Electric Plant were used for this program. During the first half of the research, a refuse handling and furnace feed system consisting of agriculture crop handling equipment was used. With this equipment the feasibility of blowing shredded refuse into a boiler and burning it completely on a traveling grate was demonstrated. Corrosion probe exposures were used to show the effectiveness of cofiring to reduce short-term corrosion of boiler tube metals. Reduced emissions of SO_2 from the high-sulfur coal also resulted from dilution of the coal with refuse and by action of alkaline components of the refuse.

To study the handling and combustion of larger amounts of shredded refuse and to measure long-term corrosion effects, an improved system was developed and installed during the second half of the program. This system consisted of a hydraulic push-pit, augers, and a belt to convey the refuse to air-swept spouts that injected the refuse into the boiler. Amounts of refuse up to 6800 kg/hr (7.5 tons per hour) were burned successfully using this system.

It was demonstrated that 700-hour corrosion rates with an average of 22 weight percent refuse and high-sulfur coal were 5 to 10 times less than those with bulk refuse burning and about equal to those from coal alone. Sulfur dioxide emissions were reduced as a function of the refuse content of the mixture. The cofiring with refuse had no significant effect on particulate loading of the flue gases, fly ash resistivity, or grate ash composition, but the ash fusion temperature was lowered somewhat.

It is recommended that further development of the cofiring in stoker-fired boilers be encouraged both for energy recovery and for reduction of landfill requirements.

This report was submitted in fulfillment of Grant No. R804008-02-2 by the Columbus Laboratories of Battelle Memorial Institute under the sponsorship of the U.S. Environmental Protection Agency. This work was conducted during the period September 1, 1974, and October 31, 1977.

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SECTION I

INTRODUCTION

The objective of this research program was the development of technology for the utilization of municipal refuse as a supplementary fuel in coal-fired power or steam generating plants. Three aspects of this technology have been investigated: (1) the preparation and handling of the refuse before burning, (2) the corrosivity of the mixed fuel to boiler tubes, and (3) the emissions and residues resulting from the burning of the mixed fuel. As a result of previous Battelle investigations which demonstrated that the corrosivity of the combustion products from municipal solid waste could be reduced by the addition of sulfur, it was proposed that disposal of municipal refuse in boiler furnaces utilizing high-sulfur coal would not be detrimental to boiler tubes. In addition, the dilution of the coal with the refuse and the reaction of sulfur oxides with alkaline components of solid waste would reduce the sulfur oxide emissions to a permissible level.

To substantiate the above concept and to develop technologies associated with the utilization of solid waste as a fuel, the Battelle Columbus Laboratory program consisted of investigating the effects of operational variables on emissions, corrosion, combustion, and ash properties in the Columbus, Ohio, Municipal Electric Plant's spreader-stoker-fired boiler furnace. This site was selected to represent coal-fired boiler furnaces with grates on which final burnout of the refuse could occur.

Although a program on burning of processed (shredded and classified) solid waste was conducted at the Union Electric Company in St. Louis, Missouri, and exists at the Ames, Iowa, Electric Utilities, the Battelle program was directed toward determining the limitations and the benefits of burning the shredded solid waste with high-sulfur coal with very little or no processing of the solid waste except for shredding. The deletion of the classification steps in the processing made it mandatory to investigate methods for receiving, storing, retrieving, and handling the refuse within the confines of the limited space available at the plant. This work had to be accomplished before the investigation of corrosion and emissions from the cofiring process could be evaluated.

During the first year of this program a temporary system for handling and feeding the shredded waste to the boiler was assembled utilizing commercially available agriculture equipment for handling forage and grain crops.

During the period of development of the above refuse handling system shredded refuse from Willoughby, Ohio, and from St. Louis, Missouri, was obtained for evaluating the equipment capabilities. Preliminary corrosivity studies on the combined fuel and the baseline coal fuel were conducted during the first year. However, the Sanitation Division of Columbus, Ohio, started operation of their Jeffrey shredders in June, 1975.

Hence, the second year of this research was directed towards utilizing Columbus refuse as a supplement to the coal fuel and evaluating the handling of this refuse plus analyzing the emissions and the corrosivity as it was burned with high-sulfur coal. In addition, the analysis of a refuse handling system for the Columbus, Ohio, Municipal Electric Plant was directed toward the design and construction of a more rugged system that would permit long-term investigations of stack emissions and fireside corrosion.

The third year of the program consisted of: (1) procuring and installing the refuse handling system, (2) optimizing the operation of the system, (3) conducting long-term corrosion runs, and (4) making additional measurements of emissions and residue characteristics.

SECTION 2

CONCLUSIONS

The experimental program conducted at the Columbus, Ohio, Municipal Electric Plant has demonstrated the technical feasibility of mechanical handling and furnace feeding of shredded municipal solid waste at an existing stoker-fired boiler with limited space and accessibility. It also has been shown that the refuse can be burned completely on a grate in conjunction with coal, utilizing a spreader-stoker. The corrosivity of the combustion products from refuse burned with high-sulfur coal was reduced significantly from that for refuse alone and was essentially attributable to the sulfur in the coal. The sulfur oxide emissions were reduced by dilution of high-sulfur coal with a very low-sulfur fuel and by the formation of stable sulfate particulate compounds with alkaline refuse components. The ash residues from the cofiring of refuse and coal had essentially the same composition as those from coal alone.

The following specific conclusions can be reached:

(1) The corrosivity of combustion products from cofiring refuse and 3 percent sulfur coal up to a 2 to 1 weight ratio is not significantly different from that of coal alone.

(2) The corrosion rates of boiler tube metals decrease rapidly with exposure time. After 700 hours, the rates for stainless steels level off.

(3) Boiler tube metals can be ranked in the following order of increasing resistance to corrosion: A106 carbon steel, P9 low alloy steel, and Types 316, 347, and 310 stainless steel.

(4) Reductions of SO_2 as much as 10 percent more than the dilution effect can be achieved under optimum combustion conditions.

(5) Refuse can be burned with coal on a traveling grate with processing limited to shredding and magnetic separation.

(6) The ash fusion temperature was reduced by burning large amounts of refuse with the high-sulfur coal.

(7) Refuse which has undergone shredding and magnetic separation can be handled effectively with augers and belts. A live-bottom feed from storage is preferable to hydraulic ram feed.

(8) The processed refuse can be fed successfully into the traveling-grate furnace with air-swept spouts.

(9) The shredded refuse nominally 10 cm (4 inches) will burn out completely on the traveling grate. The underfire air supply is a critical factor in the quality of the refuse combustion.

(10) The aluminum and other low-melting metals present in unclassified waste may cause clogging of the grates if the underfire air is not properly maintained.

SECTION 3

RECOMMENDATIONS

It is recommended that further development of the burning of shredded refuse with coal on a grate in existing boilers be encouraged, both to recover energy and to minimize landfill requirements.

In addition, the corrosivity of the combustion products of shredded and magnetically separated refuse should be investigated when such refuse is burned alone. Such data have not been obtained, and it is possible that the shredding process and removal of ferrous metals will influence the corrosion reactions sufficiently to reduce metal wastage to that experienced with coal alone.

The corrosive effects of burning very large amounts of refuse (90 weight percent) with high-sulfur coal also should be determined. The maximum refuse input without serious corrosion is not known.

Additives other than sulfur to combat corrosion should be sought for situations such as bulk burning of refuse or where high-sulfur coal is not readily available.

The combustion conditions for shredded refuse and coal should be investigated further to optimize the reduction in sulfur dioxide emissions and to minimize the particulate loading of the flue gases.

SECTION 4

BACKGROUND: CORROSION FROM BURNING OF BULK REFUSE

In previous work conducted by Battelle Columbus Laboratories at the Miami County, Ohio, incinerator under the sponsorship of the U.S. Environmental Protection Agency Solid Waste Research Laboratory, corrosion of boiler tube metals from burning of bulk municipal refuse was studied.[1] This incinerator was a refractory wall type without steam generation, but the furnace atmosphere was found to be typical of refuse burning. Consequently, Battelle-designed corrosion probes comprising various specimens at controlled metal temperatures were exposed to the incinerator environment.

Corrosion probe exposures up to 828 hours were carried out, and the corrosion rates of the various steels used as specimens were determined by the weight losses that resulted from the exposure. The weight losses increased with temperature and were especially high for carbon steel and low alloy steel. Over a metal temperature range of 121 to 649 C (250–1200 F) the high-chromium ferritic and austenitic stainless steel showed the best corrosion resistance. As a function of exposure time, the corrosion rate of carbon steel was found to be very high initially and then to drop rapidly, leveling off after about 800 hours.

Both the bulk deposits and the corrosion product layers formed on the specimens were analyzed during this program to determine the reactions leading to metal wastage. The deposits were removed from all the probe specimens in numbered sequence. Thus, the variations in composition could be determined as a function of temperature when the deposits were analyzed. Emission spectrography and wet chemical techniques were used to determine the concentration levels of the various elements in the deposits. Electron microprobe analysis and X-ray diffraction were used to obtain additional detailed information on the nature of the deposits. Analyses of the bulk deposits showed that chloride accumulated rapidly even at moderate HCl concentrations in the flue gases. Chloride concentrations ranging from 21 to 27 percent by weight were found on probes which were exposed for short periods of time ranging from 1.5 to 25 hours. Flue gases contained from 40 to 140 ppm HCl (corrected to 12 percent CO_2) during the time that these deposits were formed.

Eight analyses of typical refuse samples from the incinerator showed that the chloride content of the solid waste on a dry basis ranged from 0.32 to 0.79 weight percent, with an average of 0.49 percent. Based on an average 24-hour processing of 136,080 kg (150 tons) of waste at this incinerator, there would be about 682 kg (1500 pounds) of chlorine in the refuse. The sources of the chlorine are both inorganic, primarily as NaCl, and organic, with polyvinyl chloride plastic the predominant item. Practically all of this chlorine is volatilized at combustion temperature as the ash contains only 0.01 to 0.02 weight percent chlorine.

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[1]Miller, P. D., et al., Corrosion Studies in Municipal Incinerators, EPA-SW-72-3-3, U.S. Environmental Protection Agency, Cincinnati, Ohio, 1972, 130 pp.

As the exposure time increased and the deposit aged, the amount of chloride decreased. This change resulted from the action of SO_2, which converted the chlorides to sulfates. A temperature effect also was observed because the amount of chloride generally was greatest in the deposits found on lower temperature specimens. Average chloride values in bulk deposits of long-term runs ranged from a few tenths of a percent at temperatures from 399 to 677 C (399–1250 F) up to 3.8 percent in the 121 to 260 C (250–500 F) temperature zone. However, the chloride was not equally distributed throughout the deposit, and the bulk of it diffused into the layer at the metal-deposit interface. The deposits from the 828-hour probe exposure, which showed a uniform low average chloride content of 0.2 weight percent, were sectioned horizontally to separate the bulk of the deposit from the corrosion product scale at the interface with the metal. Analyses of the two sections of the deposit demonstrated that the chlorine was concentrated in the inner layer. The outer layer contained only 0.2 weight percent chlorine while the inner layer showed values up to 4.2 weight percent. The other elements which were found to be concentrated in the inner layer were sulfur, potassium, lead, zinc, and iron.

Investigation by X-ray diffraction has demonstrated that a continuous layer of $FeCl_2$ exists at the interface with the metal. FeS occurs between the $FeCl_2$ and the overlaying Fe_2O_3 layer. Various other compounds, mostly sulfates, were identified in the deposits. About 20 different compounds have been identified (Figure 1). On the higher temperature specimens, it was found that the $FeCl_2$ layer melted and collected into small pools. The electron microprobe showed that a zinc compound was also present in this area near the metal. It appears that this element is not in a form readily detected by X-ray techniques but may be incorporated in the $FeCl_2$ or in the FeS as a replacement for some of the iron atoms in the host structures. These interface layers are some 6 to 10 microns thick on the low temperature specimens. The thickness increased somewhat with temperature.

Between the interface scale and the bulk deposit was a multilayered scale of Fe_2O_3 and Fe_3O_4. It is interesting to note that a thin layer of alpha-Fe_2O_3 formed at the interface between the $FeCl_2$ and mixed oxides. At low temperatures FeS forms between the $FeCl_2$ and Fe_2O_3 layers. Part of the mixed oxide scale adhered to the substrate and part to the external deposit. The mixed oxide layer was a hard, brittle, magnetic, gray-black material which thickened with temperature and was made up of several layers with loose red Fe_2O_3 layers. This suggests that reduction or reaction with other elements occurs in or below this layer. At the higher temperature, where $FeCl_2$ melts and FeS forms on the substrate, the mixed oxide scale was less adherent, and in this area more of the mixed oxide was removed with the outer deposit.

Examination with the optical microscope indicated that some melting had occurred in the deposit near the mixed oxide scale. These studies showed the presence of recrystallized continuous phases of the compounds $(Na, K)_2SO_4$ and $PbO{\cdot}PbSO_4$ on the external surface of the mixed iron oxide scale. The sodium-potassium sulfate phase was also dispersed throughout the iron oxide scale and adhered to the bulk deposit. It appears that separation in the iron oxide scale occurred at the depth to which this salt phase permeated in sufficient quantity to destroy the iron oxide. It is proposed that in the initial stage of incinerator operation these salt phases as well as mixed alkali chloride salts and possibly $ZnCl_2$ and $PbCl_2$ permeate the iron oxide scale and destroy its protective characteristics.

The flue gas compositions in the vicinity of the corrosion probes were measured in order to determine the gaseous environment to which these specimens were subjected. The range of values found for the various components is presented in Table 1 HCl was by far the main component found in the flue gases, with the SO_2 concentration significantly lower. The other gaseous components found in the furnace were not considered to be making any significant contribution to corrosion.

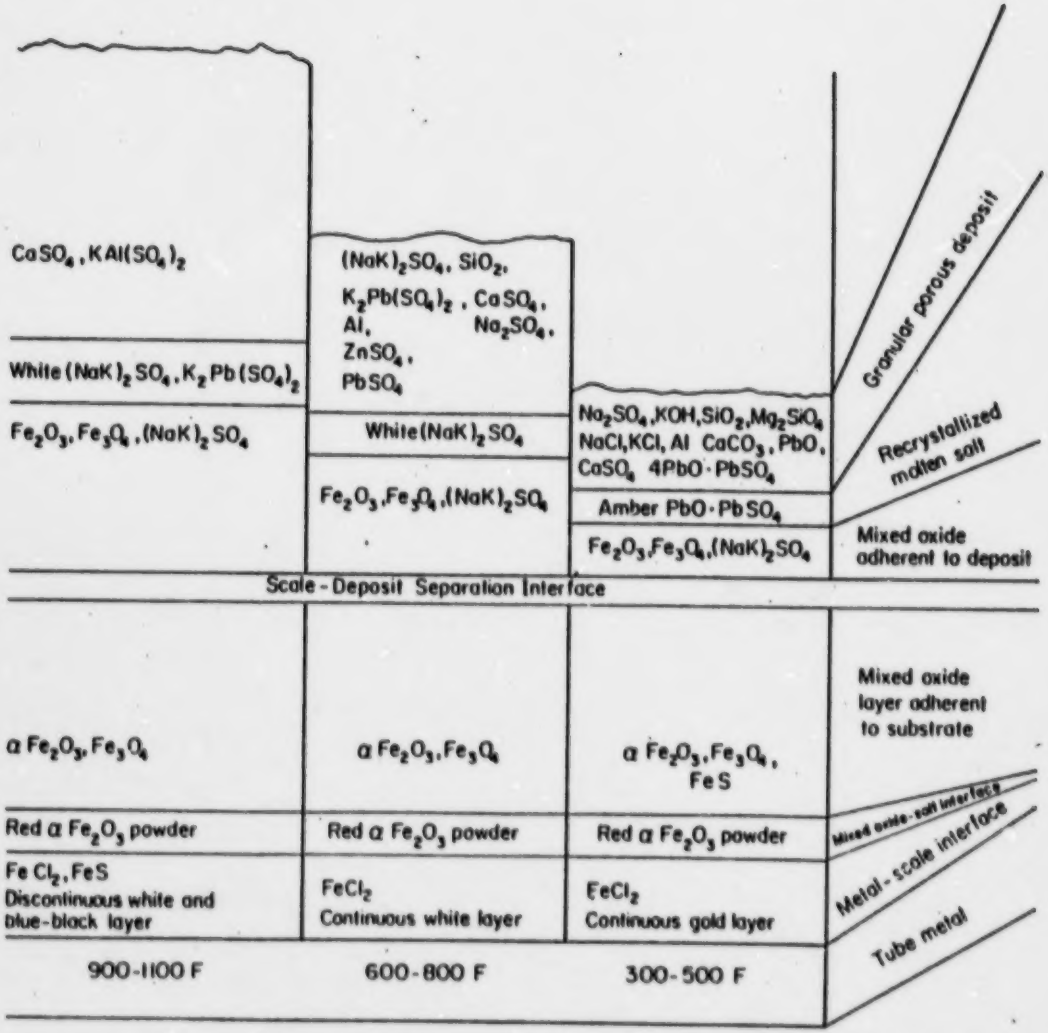

Figure 1. Schematic location of phases identified by X-ray diffraction.

TABLE 1. CONCENTRATIONS OF CHEMICAL SPECIES IN INCINERATOR FLUE GASES[a]

(In dry gases, corrected to 12 percent CO_2)

Component	Range of concentration, ppm
Sulfur dioxide, SO_2	59 - 195
Chloride, Cl^-	214 - 1250
Fluoride, F^-	3 - 34
Nitrogen oxides, as NO_2	53 - 115
Phosphate, $PO_4^{\equiv}$	0.5 - 6
Organic acids	35 - 178
Aldehydes and ketones	1 - 12

(a) From measurements made in the furnace at Miami County, Ohio, Oceanside, N. Y., and Norfolk, Va.

A number of chemical reactions are proposed to account for the formation of chlorides and sulfates in the deposits (Figure 2). Initial deposits are alkali metal oxides, which are then converted to chlorides by the action of HCl. Some chlorides such as NaCl may be volatilized in the flame and deposited as such. It is believed that corrosion is initiated when chlorides are converted to sulfates by the action of SO_2, oxygen, and moisture, thereby releasing HCl and chlorine at the metal surface. The hydrogen chloride formed can then react with the iron surface to form ferrous chloride, or it may be oxidized to elemental chlorine. As indicated by the laboratory studies at Battelle and supported by the work of Brown, DeLong, and Auld[2], the corrosive effects from HCl would not be expected to be severe below temperatures of about 399 C (750 F). Since $FeCl_2$ has been detected on corrosion probe samples exposed to temperatures well below 399 C (750 F), it is likely that corrosion by elemental chlorine is operating in the lower temperature range. Although elemental chlorine has not been identified in incinerator and furnace gases, it is believed that it may play a major role in the corrosion reaction beneath the deposits.

The molten salt phase, which was found as an interface layer between the scale and deposit, would act as a barrier to the motion of gases in and out of the layer adjacent to the metal surfaces. Under oxidizing conditions, it would be expected that $FeCl_2$ would react with oxygen to form Fe_2O_3. Once a scale formed on the metal tubes, such a cyclic reaction could occur. The mixed oxide in molten salt layers would limit the availability of oxygen and retain the chlorine within the adherent scale. Similar corrosive conditions from deposited chloride were demonstrated by Cutler, et al.[3], particularly as they applied to burning fossil fuels containing chlorine. The possibility of oxidizing $FeCl_2$ to release elemental chlorine also was shown by Fassler, et al.[4]

[2]Brown, M. H., DeLong, W. B., and Auld, J. R., Corrosion by Chlorine and by Hydrogen Chloride at High Temperatures, *Journal of Industrial and Engineering Chemistry*, 39, July, 1947, 839-844.

[3]Cutler, A.J.B., Halstead, W. D., Laxton, J. W., and Stevens, C. G., The Role of Chloride in the Corrosion Caused by Flue Gases and Their Deposits, ASME Paper No. 70-WA/CD-1, Winter Annual Meeting, New York, December, 1970.

[4]Fassler, K., Leib, H., and Spahn, H., Corrosion in Refuse Incineration Plants, *Mitt. V.G.B.*, 48, April, 1968, 126-139.

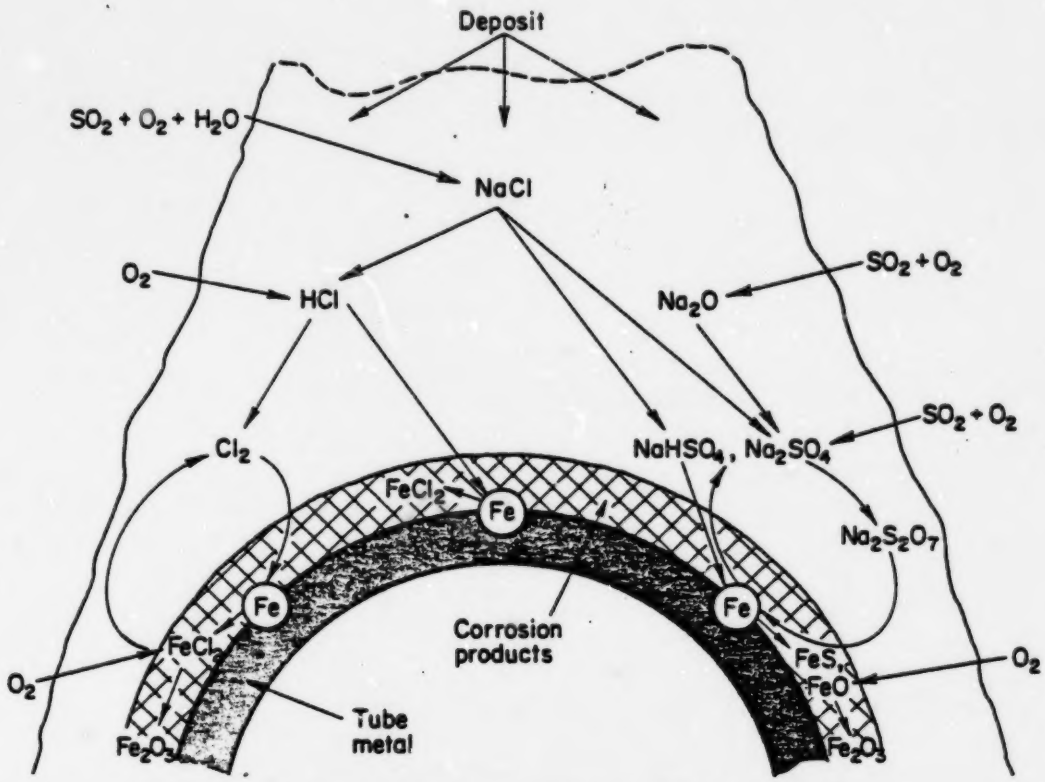

Figure 2. Sequence of chemical reactions explaining corrosion on incinerator boiler tube.

The formation of FeS in the corrosion product layer indicates that sulfur is also playing a part in the corrosion reactions. The alkali pyrosulfates and bisulfates are known to be very corrosive materials, and the potassium compounds in particular have low melting points. Hence, corrosion by these materials is a very likely possibility for the formation of FeS. The corresponding sodium compounds have somewhat higher melting points, but it is possible that the melting point of these salts may be lowered in the deposits by the zinc and lead compounds which are known to be present on the corroded samples.

To make a more complete evaluation of chlorine and sulfur in the corrosion reactions, the concentration of these elements in the refuse was increased by the addition of either polyvinyl chloride (PVC) or elemental sulfur. Since it was not feasible to conduct experiments with controlled additions of these materials over long periods of time, this program consisted of exposing corrosion probes for 10 hours. These short-time experiments were intended to show differences in the corrosiveness of the combustion environment as the result of the increased concentration of chlorine or sulfur. With an increase in chlorine content of the refuse by PVC addition, the corrosion rate increased sharply above the metal temperature of 427 C (800 F). The effect of adding polyvinyl chloride to the refuse is shown in Figure 3. At all temperatures the corrosion rate increased rapidly with the initial additions of PVC. After the amount added reached 0.5–1 percent

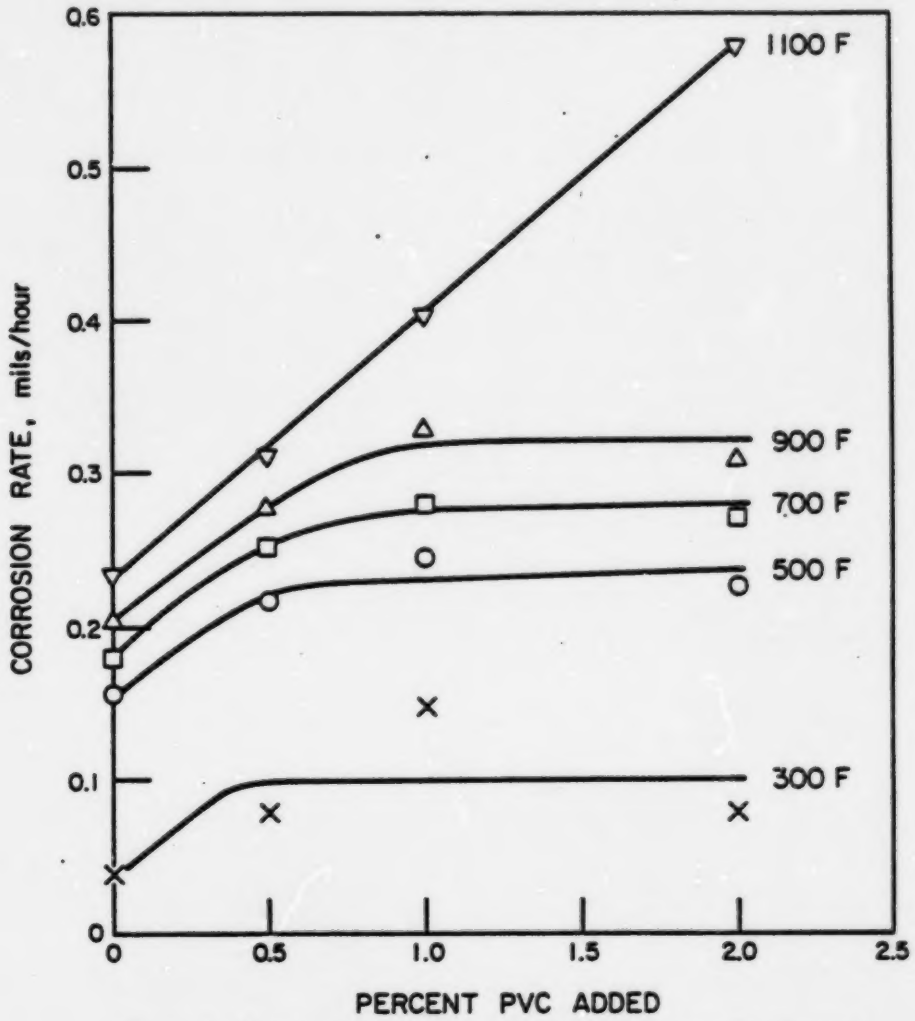

Figure 3. Isothermal corrosion rate of A106 steel versus percent PVC added to refuse.

the corrosion rates leveled off at metal temperatures up to 482 C (900 F). However, at a metal temperature of 593 C (1100 F) the corrosion rate continued to increase linearly with the amount of PVC added.

When sulfur was added to the refuse, the chloride content of the deposits decreased significantly (Table 2). The effect was particularly pronounced in the 371 to 399 C (700-750 F) temperature zone where chlorine reached a concentration of 7.5 weight percent in the deposits after 8 hours of operation with normal refuse. When 0.75 weight percent sulfur was added to the refuse, the chloride concentration dropped to 1.9 percent; when 1.5 weight percent sulfur was added, the chloride concentration was further reduced to 0.1 weight percent. The effect was even more pronounced in the high temperature zone where the chloride concentration was reduced 25-fold by the addition of 0.75 weight percent sulfur and below the detection limits for chloride when 1.5

TABLE 2. SULFUR AND CHLORINE CONTENT OF DEPOSITS WITH SULFUR ADDITIONS TO REFUSE

	Concentration (wt %) with indicated sulfur addition (wt %)					
	None		0.75% S		1.5% S	
Element	745 F[a] (395 C)	1120 F (605 C)	730 F (390 C)	1125 F (605 C)	740 F (393 C)	1175 F (635 C)
Sulfur	4.6	2.8	3.5	6.0	5.0	3.8
Chlorine	7.5	2.5	1.9	0.1	0.1	< 0.1

(a) Metal temperature.

weight percent sulfur was added. This decrease in the chloride concentration in the deposits indicates that the added sulfur in the refuse rapidly forms sulfur oxides, which then react with the metal chlorides while still in the flue-gas stream. This rapid formation of sulfates left very little particulate chloride to collect in the deposit. The effect of the sulfur additions on the corrosion rate of A106 steel is presented in Figure 4. At 149 C (300 F) metal temperature the corrosion rate decreased linearly with the amount of sulfur added. At higher temperatures the rapid decrease in corrosion rate began at the point of 0.75 weight percent sulfur addition. On the basis that the normal sulfur content of refuse is about 0.2 percent, these data indicate that when the total sulfur level in the refuse reaches 1 percent, the corrosion rates can be expected to decrease.

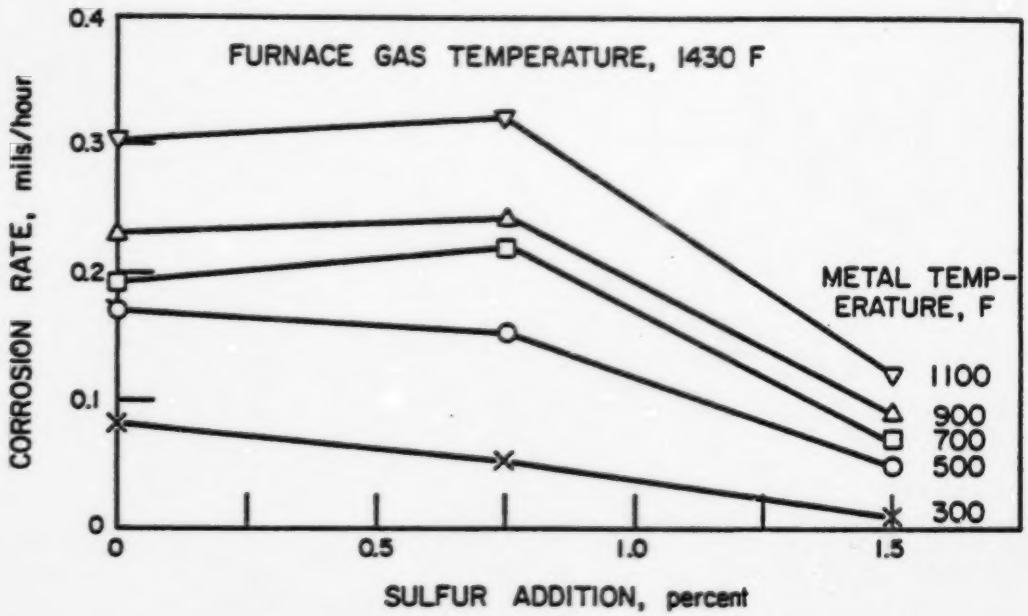

Figure 4. Effect of sulfur additions to refuse on the corrosion rate of A106 carbon steel.

An even more dramatic effect of sulfur addition to the refuse was found with Type 316 stainless steel, as indicated in Figure 5. At 427 C (800 F) the corrosion rate decreased by about an order of magnitude when 0.75 percent sulfur was added to the refuse, but no further decrease was noted with additional sulfur. The corrosion rates at 538 and 649 C (1000 and 1200 F) decreased about 25- and 30-fold, respectively, with the 0.75 percent sulfur addition. There was a slight increase in the corrosion rate at 649 C (1200 F) when the sulfur addition was increased to 1.5 percent. There also were significant decreases in the corrosion rate of ferritic stainless steels when sulfur was added to the refuse.

The experimental data showed that the reduction in corrosion rates during the addition of sulfur to the refuse was accompanied by a significant reduction in the chloride content of the deposits and of the particulates extracted from the furnace or the stack. These observations indicate that the following chemical reaction is occurring in the flue gas stream rather than in the deposit:

$$\text{Metal chloride} + SO_2 + O_2 + H_2O = \text{metal sulfate} + HCl \text{ or } Cl_2 \quad .$$

Because the corrosive chlorine-containing agents are released in the gas stream, they do not have the opportunity to act on the metal as they would by in situ formation beneath the deposit which adheres strongly to the tube metal. It also was noted that when sulfur was added to the refuse, the deposits formed on the corrosion probe were of a light powdery nature and much less adherent than in the case when normal refuse was burned. The conversion of the metal chlorides to metal sulfates before deposition on the tubes would account for this effect and would result in the presence of compounds in the deposit which have much higher melting points than the corresponding chlorides.

The addition of sulfur to the refuse produced a sharp decrease in the corrosion rates of all types of steel investigated. In the case of low alloy steel, sulfur addition must be sufficient to reduce the chloride content of the initial deposit to the 0.1 percent level in order to achieve low corrosion rates. It is believed that the sulfur content of the refuse must be about 2 percent to achieve this low chloride level in the deposits, thus eliminating corrosion from this source.

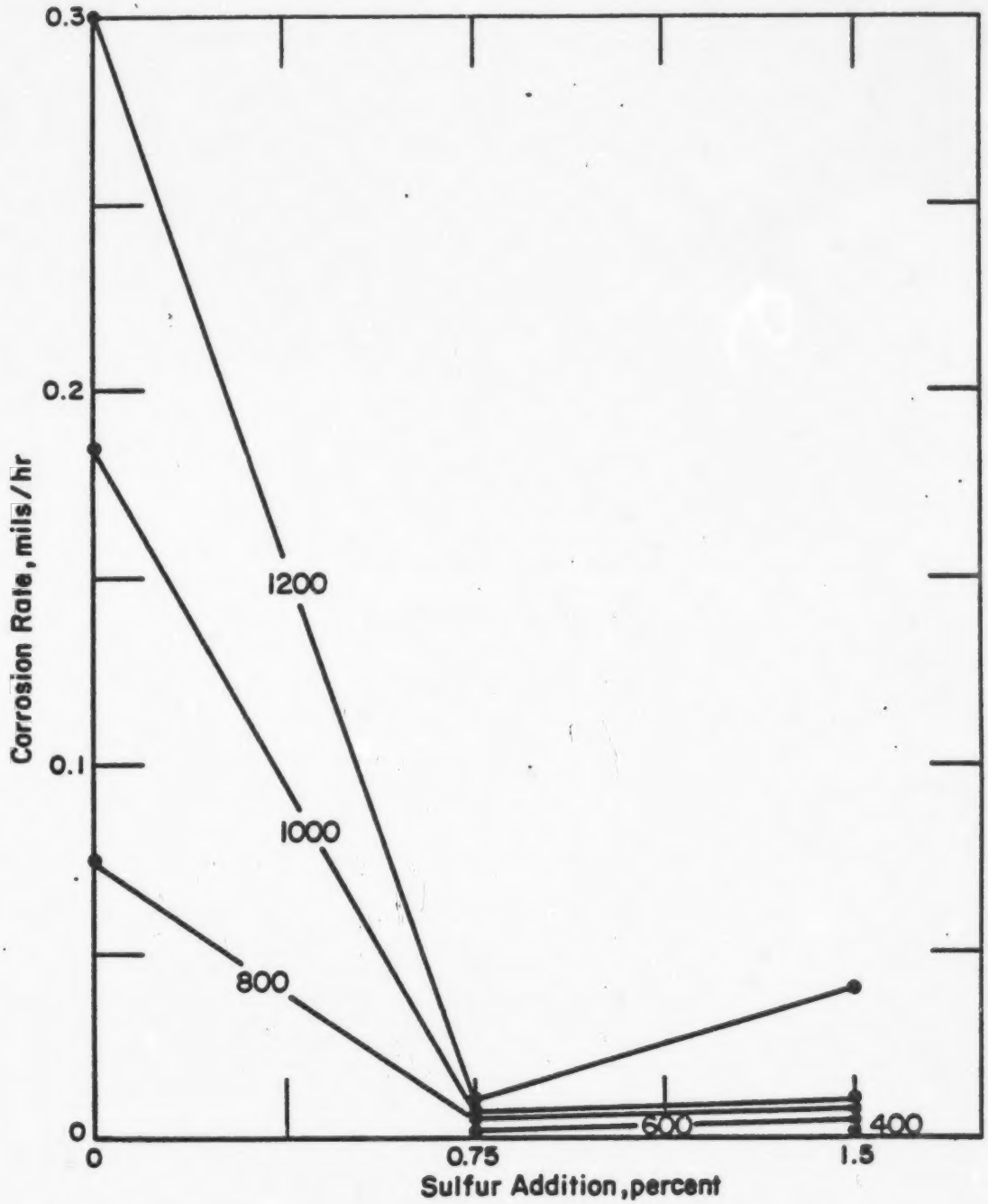

Figure 5. Effect of sulfur additions to refuse on the corrosion rate of Type 316 stainless steel.

SECTION 5

REFUSE HANDLING SYSTEM

Shredded refuse is generated at three shredder stations in Columbus, Ohio, at a rate of 3.6 to 4.5 x 10^4 kg (40 to 50 tons) per hour each, operating 7 hours per day, 5 days per week. These shredders have a capacity of 54,500 kg (60 tons) per hour with screens of 13 x 15 cm (5 x 6 inches) which produce 90 to 95 percent minus 10 cm (4 inches) product. The remaining 5 to 10 percent of the product may vary in one dimension up to 46 to 51 cm (18 to 20 inches) even though the other dimensions may not exceed the nominal 10 cm (4 inches).

Transfer trucks normally haul this refuse to landfill but by request would deliver it in 1.4 to 1.8 x 10^4 kg (15 to 20 tons) loads to the Municipal Electric Plant. The Sanitation Division transfer trucks should be emptied in 20 to 30 minutes during the daytime to avoid delaying shredder operation but could be used for storage and/or retained for longer periods at night. As described below, the refuse burn rate at the power plant was not expected to exceed 9.07 x 10^3 kg (10 tons) per hour, which would require approximately 2 hours to use a 15 to 20-ton truckload of refuse.

The Columbus, Ohio, Municipal Electric Plant boiler furnace No. 6 (Riley) is coal fired with five Riley spreader stokers and has a rating of 68,000 kg (150,000 pounds) of steam per hour but normally operates over the range of 32,000 to 57,000 kg (70,000 to 125,000 pounds).

Assuming an average steam flow of 4.5 x 10^4 kg/hr (100,000 lb/hr) and 50 percent of the heat generated by refuse, the amount used per hour would be about 6,000 to 7,000 kg (7 to 8 tons) per hour. Thus, a truckload of refuse could be delivered to the power plant every 2 to 3 hours during the day, and perhaps through the night if the refuse is reserved in the trucks for this purpose from the daytime operation of the shredders. Alternatively, a storage facility for 11 to 13 x 10^4 kg (120 to 140 tons) of refuse would be needed at the plant site.

A plan view of the site is shown in Figure 6 before installation of any of the refuse handling facilities. The limited area available for storage required that the system be designed to move the refuse from the truck to the furnace with a minimum retention time.

TEMPORARY SYSTEM

The temporary system, consisting of agricultural equipment, which was used for short term (8–10 hour) runs during the first year, is shown in Figure 7. The transfer trucks delivered refuse to Power Feed Box 1 from which it passed to Box 2 at a lower level in the yard. Conveyors carried the refuse upward to a point above the boiler where an air classifier was installed.

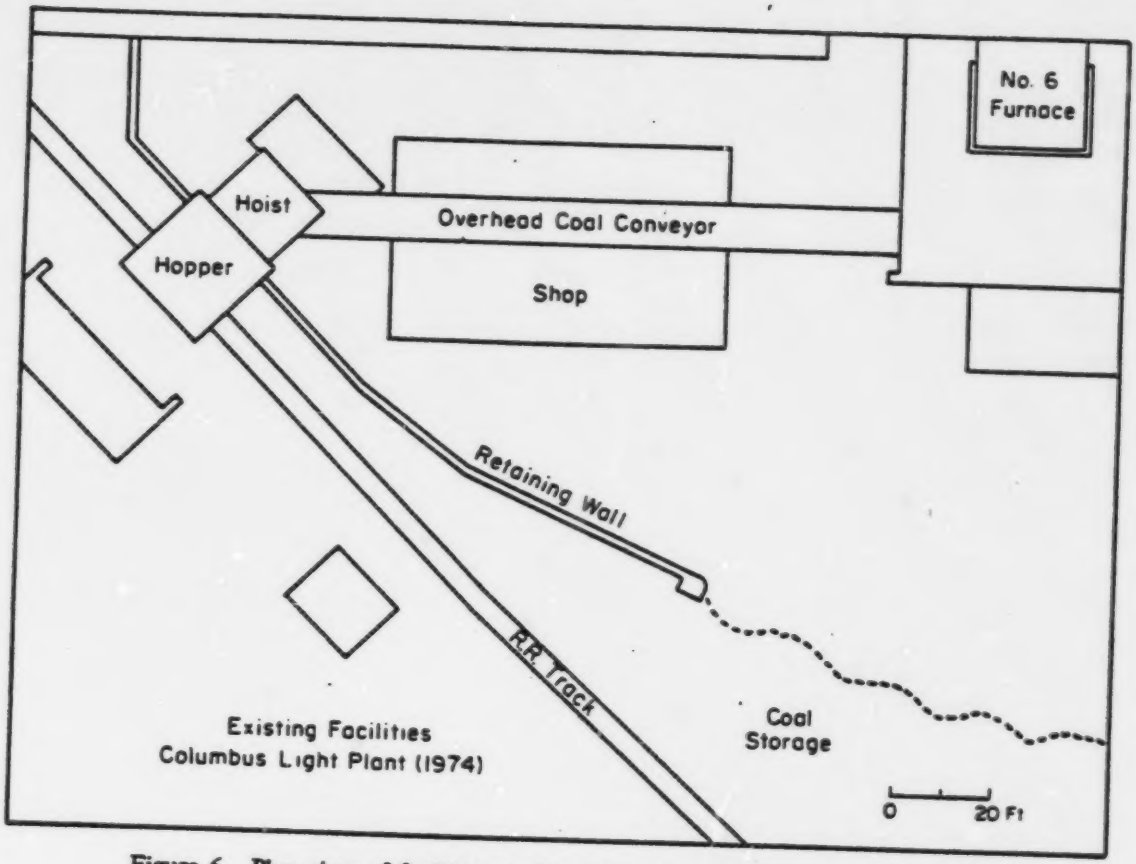

Figure 6. Plan view of facilities at Columbus Light Plant before installation of refuse handling equipment.

The refuse obtained from the Jeffrey shredders [13 x 15 cm (5 x 6 inches) grates] contains many (3 to 5 percent) pieces exceeding the nominal 10-cm (4 inches) particle size. The oversized pieces consist of rags, shoes, rubber tires, boots, limbs and wood framing, pipe, rod, and plate-shaped metal parts, plus the sponge-type plastic material. These materials interfered with the flow of the bulk of the refuse through any narrow opening or through the 0.91-m (36 inches) diameter blower fan of the furnace feed system. Therefore, either the through-fan furnace feed system had to be abandoned or the oversize and heavy pieces had to be removed. Since the conversion of the feed system to eliminate the through-fan blower would delay the program, the interim solution was to air classify the refuse immediately ahead of the blower fan. A schematic representation of this air classifier is shown in Figure 8. Here the suction of the blower fan draws the light material into the intake duct and impels it into the furnace. The heavier particles fall past the intake window and are cleaned of lighter fragments by an auxiliary air supply. The heavies then fall down the discharge tube. The light fragments, separated from the heavy particles, are propelled by jets of air up to the window area of the classifier where they are drawn into the intake duct.

The total rejects by this classifier were approximately 15 percent with as-shredded refuse, but about 5 percent of the refuse delivered after magnetic removal of ferrous metals.

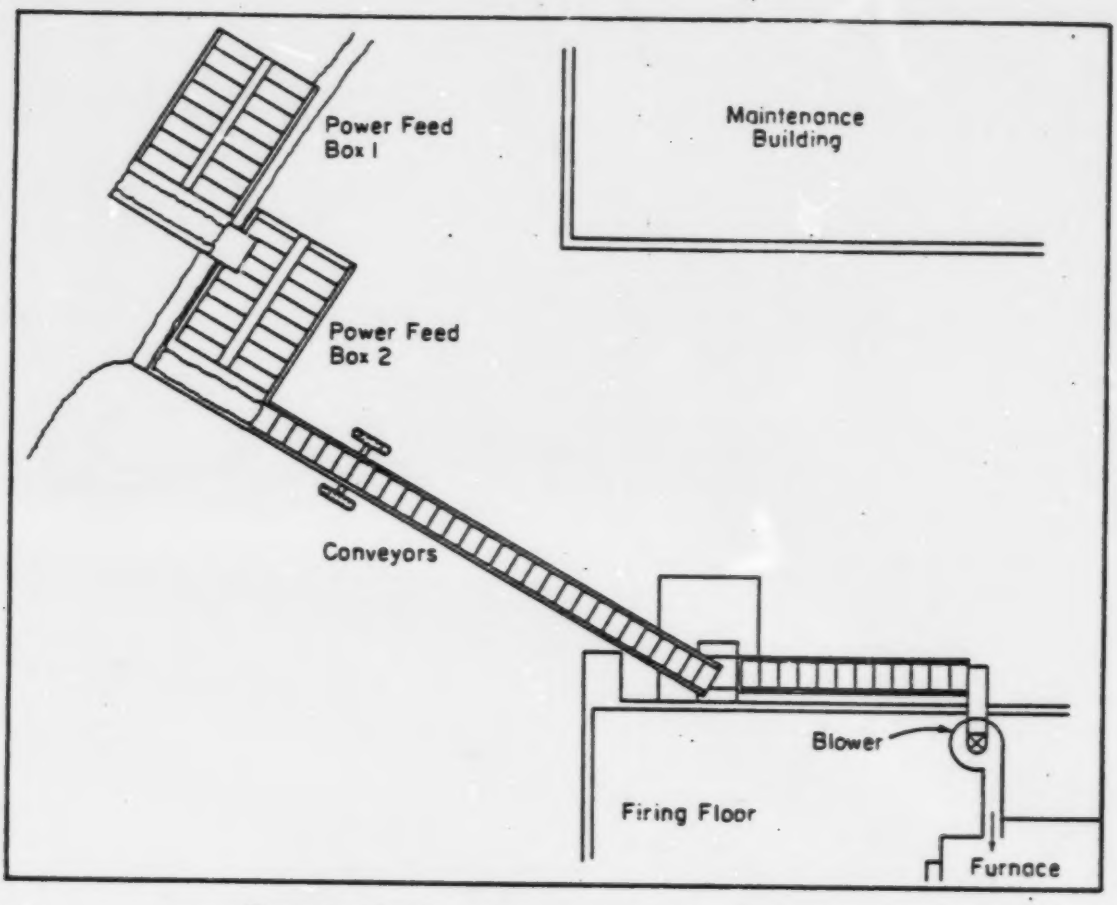

Figure 7. Sketch of temporary refuse handling system.

The air-classified refuse was then blown through an opening in the side of the furnace onto the front of the grate. The furnace feed system is illustrated in Figure 9, which shows the distribution of the refuse and the coal as it falls on the traveling grate. This grate empties at the rear of the furnace, and therefore the refuse feed was positioned near the front wall at a location where no wall tubes had to be displaced.

PERMANENT SYSTEM

Although the temporary refuse handling system operated adequately for evaluating refuse quality, for providing guidance in the design parameters of a more rugged system, and for investigating preliminary short-term corrosivity and emission, its operation required excessive operator attention. Therefore, during its operation the analysis of specific functions to arrive at a workable, permanent system for the Columbus, Ohio, facilities was conducted.

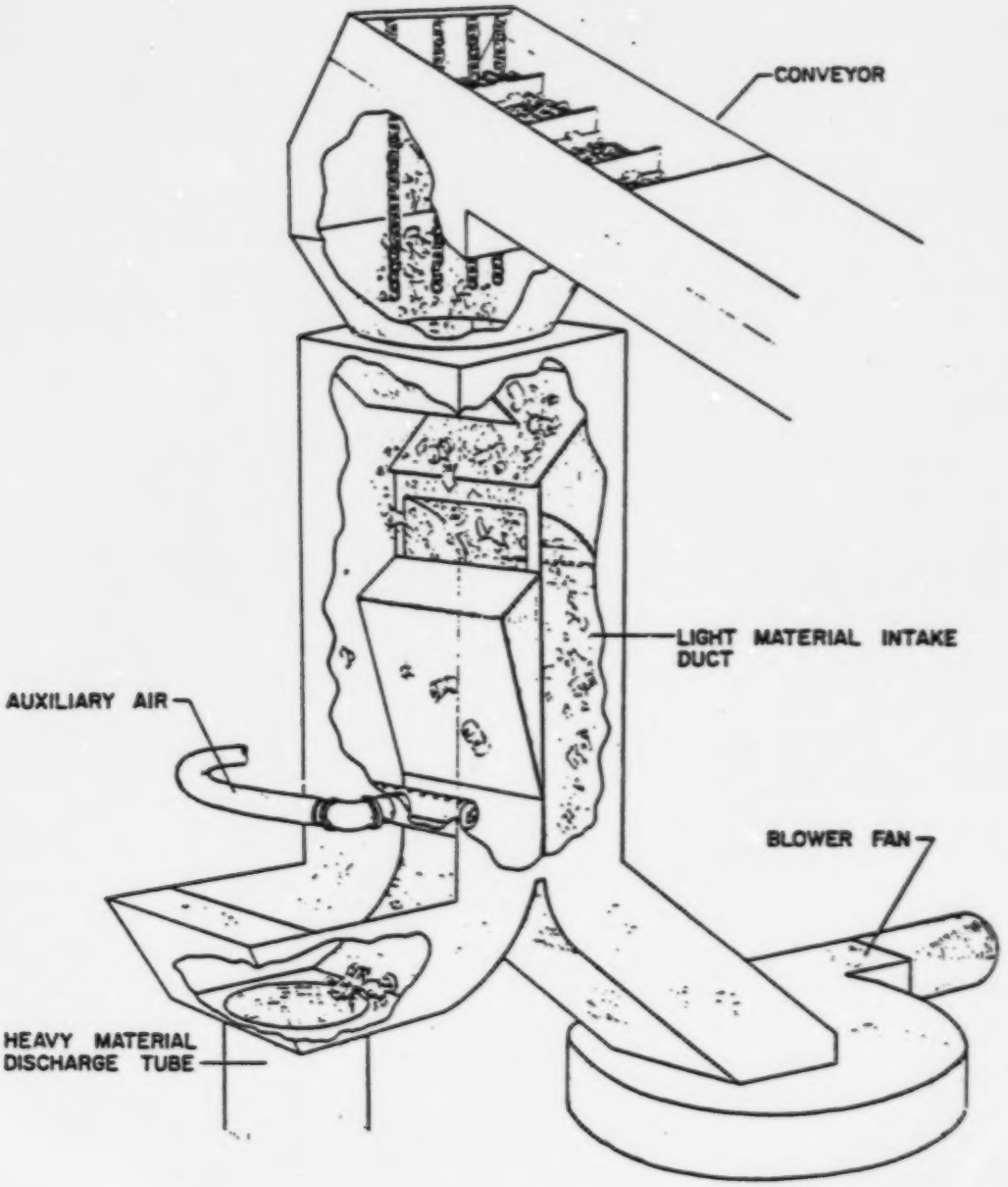

Figure 8. Sketch of in-line air classifier.

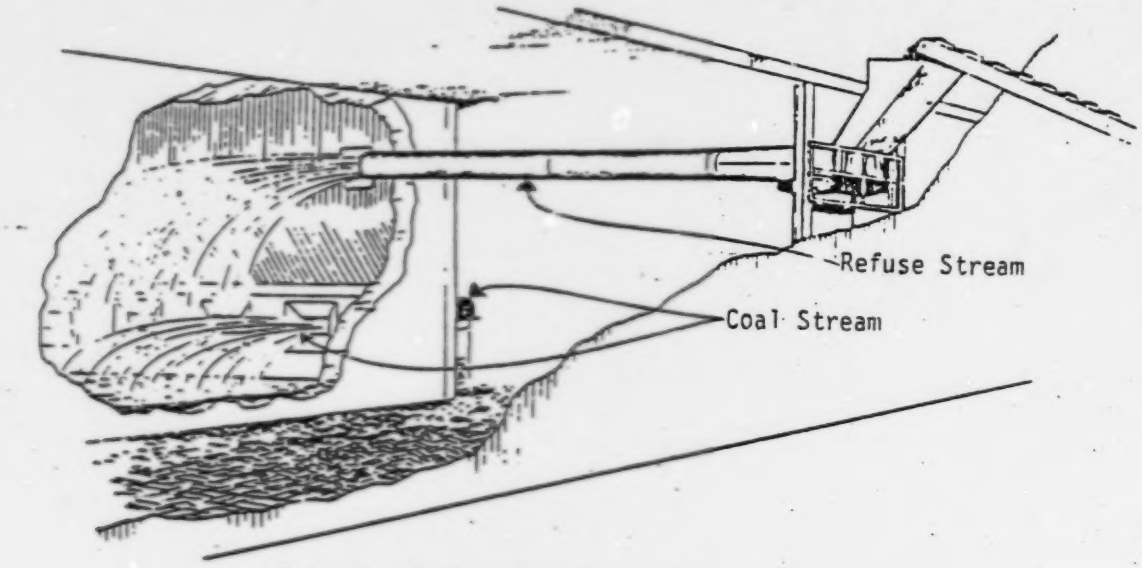

Figure 9. Sketch of through-fan furnace feed system.

Storage and Retrieval System

Several storage and retrieval systems for the refuse were considered: (1) a bottom-feed storage dome, (2) a bottom-feed silo, (3) a live-center storage bin, (4) a push-pit system with a hydraulic ram, and (5) open storage in a roofed area with use of a front-end loader. After consideration of the available space and possible equipment arrangement at the power plant, it was decided that the push-pit system would be the most suitable and cost-effective system. A sketch of the system for storage and retrieval is shown in Figure 10.

Push-Pit Operation—

The layout dictated that the push-pit be positioned at the base of the existing retaining wall. The 12.2-m (40 feet) refuse trailers back up along the upper level and are positioned at a slight angle to the side of the pit dump zone. A chute and deflector arrangement is provided so that when the truck's on-board hydraulic system pushes the refuse out of the trailer, it is directed into the push-pit dump zone.

Two persons are required for the unloading of trailers. One handles the truck while the other operates the push-pit controls. It is desirable that the push-pit be substantially empty when loading begins. With the push-pit ram in the fully retracted position, refuse from the transfer truck is fed out of the trailer and down the chute to fill the pit-load zone. The push-pit operator manually advances the ram to push the refuse beyond the load zone. A vertically operated gate separates the chute and the push-pit, preventing refuse from falling behind the ram. Three to five cycles of the ram are required to unload the 10,886–13,608 kg (12–15 tons) of refuse from the trailer, depending on the compactness and adhesiveness of a particular load of refuse.

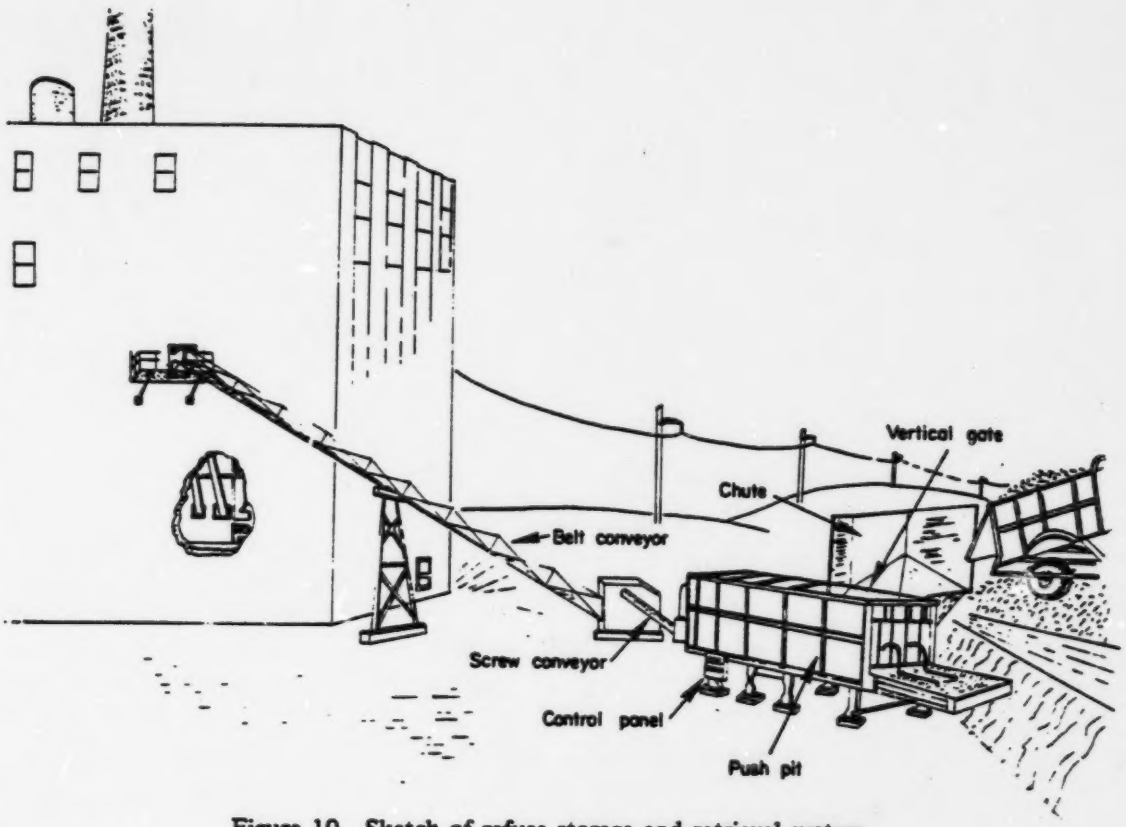

Figure 10. Sketch of refuse storage and retrieval system.

During normal "automatic" operation of the system, the push-pit ram is operated at the rate required to keep the refuse moving forward in the pit so that a body of refuse is continually presented to the reclaim system mounted on the end of the pit. The ram goes forward by small increments as determined by a timer on the hydraulic control system.

Reclaim System—

The end of the push-pit has been modified and extended to incorporate a reclaim system to feed refuse from the pit in a continuous stream.

Its trough-shaped bottom is lower than the floor of the push-pit and is fitted with a 0.4-m (16 inches) diameter screw conveyor which feeds refuse out of the box in a continuous manner. The "head" above the feed screw is maintained by the action of beater bars which break up the advancing "wall" of refuse in the front portion of the push-pit and drop it into the feed screw zone. The beater-bar motion is controlled on a demand basis according to the volume above the feed screw. In turn, the rotation of the beater bars controls the "inching" action of the push-pit ram. Should the beaters stop, which occurs if the feed screw zone is too full or the beaters are jammed, the push-pit ram is stopped immediately.

A variable-speed 0.35 m (14 inches) diameter screw conveyor redirects the flow of refuse from the feed screw and deposits the refuse on a belt conveyor. A sketch of the reclaim system is given in Figure 12.

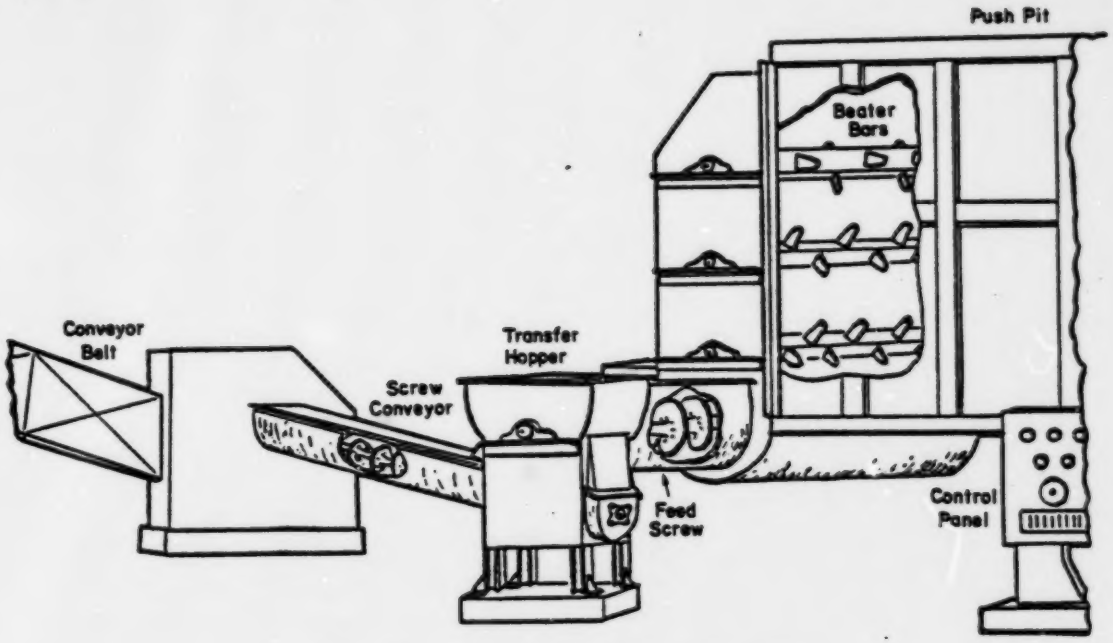

Figure 11. Sketch of refuse reclaim system.

Belt Conveyor—

The metering screw feeds the refuse at a controlled rate onto a trough-belt conveyor 0.76 m (30 inches) wide, which carries it up to a drop point just outside the wall of the boiler building at a level one floor above the furnace-feed blower. The belt moves at a speed approximately 0.48 m/s (95 ft/min) on a 21-degree angle. Its maximum volumetric capacity is 119 m^3/hr (4200 ft^3/hr) at that speed. Assuming an average refuse density of 112 kg/m^3 (7 lb/ft^3), the maximum capacity is 13,335 kg/hr (14.7 tons/hr). The belt conveyor is completely enclosed to prevent littering. Its bottom panels can be opened for cleaning or other maintenance.

Interlocks—

The entire material-handling system is interlocked electrically so that should any element be shut off or become jammed, those elements which are behind it in the system will stop. The main conveyor can be shut off by an operator at the boiler or by an operator at the push-pit. It can be restarted from the push-pit control panel.

Interface Transfer System

The interface system for transferring refuse from the belt conveyor to the two Riley air-swept spouts that feed the furnace is illustrated in Figure 12.

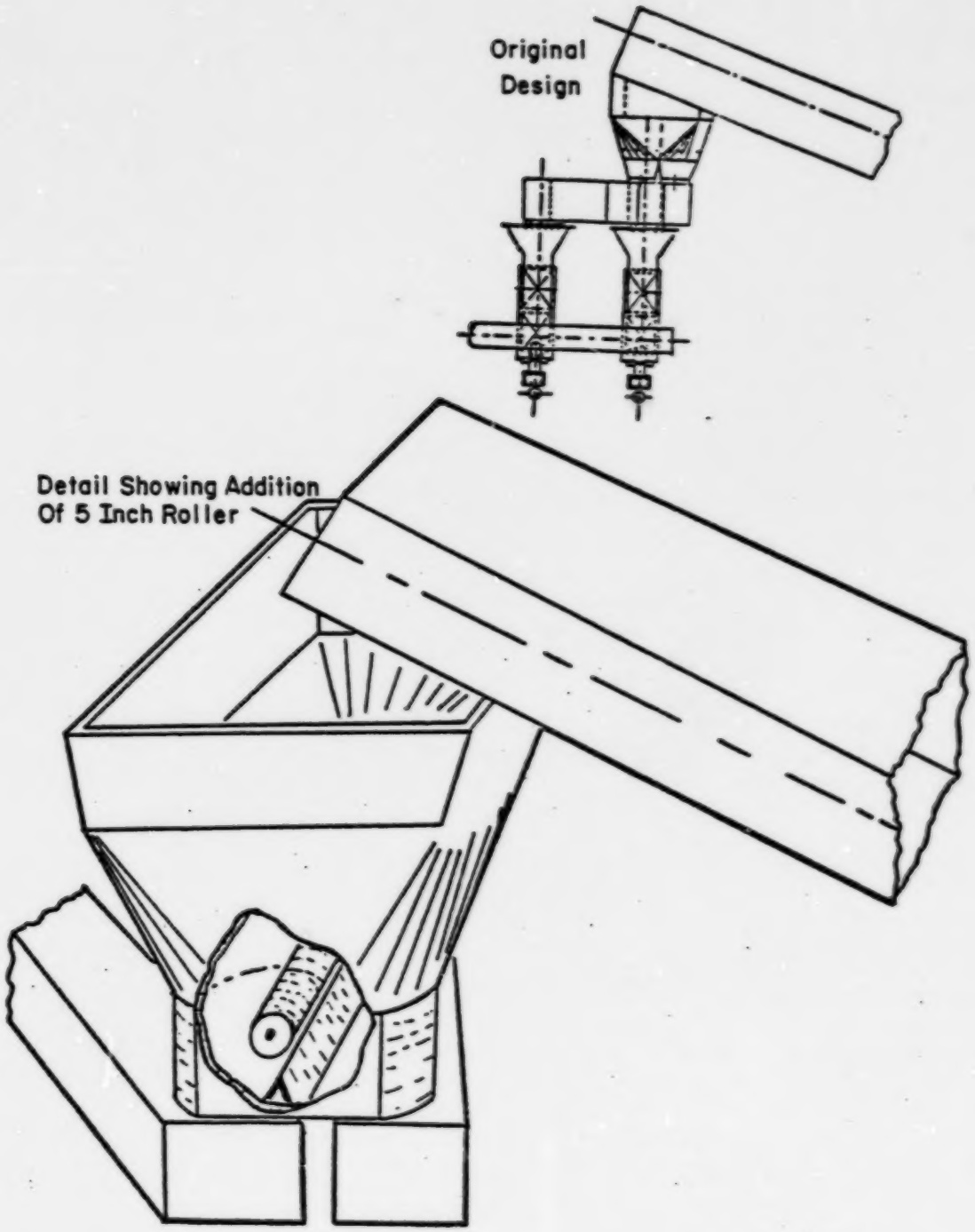

Figure 12. Interface transfer system.

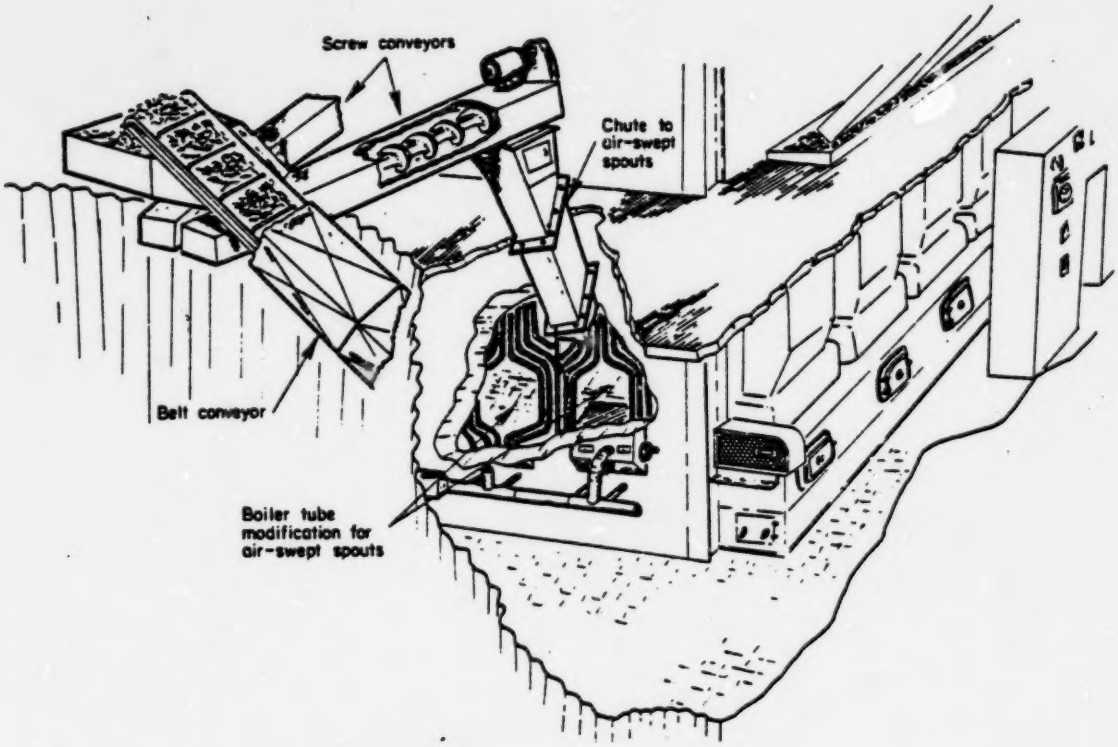

Figure 13. Sketch of furnace feed system.

To provide a uniform distribution of the refuse over the furnace grate surface, the refuse is split at the exit end of the belt conveyor and fed into two screw conveying augers. The inverted "Y" hopper receives the refuse from the conveyor belt and directs it into the two augers. The proportion fed to each auger can be selected by baffles in the upper section of the inverted "Y" hopper. These baffles are manually adjusted to feed one auger or both, depending upon the distribution needed for optimum combustion in the furnace.

The augers, which have 0.4 m (16 inches) diameter screw conveyors, are each driven by 5-hp motors through speed reducers and are capable of transferring refuse from the conveyor to the swept spouts at a rate greater than the 12,700 kg/hr (14 tons/hr) estimated capacity of the belt conveyor. Thus, it is possible to transfer the total load to either auger in the event one of the augers or one swept spout becomes inoperative. However, for normal operation the refuse is appropriately divided for optimum combustion conditions.

The augers transfer the refuse from the inverted "Y" hopper a distance of 3.66 m (12 feet) horizontally and drop it into the air-swept spouts. In the event a spout plugs, the refuse piles up at the exit end of the auger and lifts a cover which automatically stops that auger. The other auger then handles the total feed until the plug is cleared from the first spout. If both spouts become plugged, both auger trip switches open, and the entire feed system is deactivated and cannot be started until the spouts are cleared and one or both augers become operative. Very few problems have occurred, however, with the interface system operation. Long pieces of rags created plugging difficulties until a

0.13 m (5 inches) diameter roller was inserted in the inverted "Y" where the legs join. This allows the long rags to fall off as the roll turns and prevents buildup in the hopper.

The refuse drops out of the augers of the interface transfer system through chutes onto pneumatic refuse fuel distributors. The chutes are mounted at approximately a 60-degree angle to the auger so that the refuse falls by gravity down onto the feed distributor trays and is swept into the furnace by pressurized air. A rotating damper in the air distributor ducts produces pulses to vary the refuse distribution across the furnace. The fuel trajectory is controlled by angling the distributor plate either up or down. However, to maintain suspension while the refuse is burning, two air nozzles are mounted beneath each refuse feeder. These air supplies provide part of the overfire air needed for combustion while the remaining air requirements are supplied by the blower through eighteen jets mounted in the rear wall of the boiler furnace. Butterfly dampers are located in each of the air ducts to provide manual adjustment of the air for each of the three functions. Control of the eighteen overfire air jets is based upon measured oxygen excess in the combustion chamber of the furnace, which normally operates at 6 to 10 percent excess oxygen. A sketch of the furnace feed system is presented in Figure 13. Detailed drawings of the various components of the refuse feed system are given in Appendix A.

Refuse and coal were fed to the furnace separately in all but one of the runs. For Probe 31 the St. Louis refuse was mixed with coal in the bunker and fed to the furnace via the spreaders.

During the 7 months in which the permanent feed system was operated, a total of 1486 tons of shredded refuse was consumed along with 13,014 tons of coal. On a monthly basis the refuse portion ranged from 2 to 25 percent by weight. Peak rates of refuse feeding amounted to 12 tons per hour for periods of 1 to 2 hours without coal. However, on the basis of 8-hour shifts, the highest refuse feed averaged 6.4 tons per hour. During the 9 weeks of 5-day operation required for the long-term experiment, the refuse throughput generally ranged between 1 and 3 tons per hour. The amounts of fuel consumed and steam generated on a monthly basis are shown in Table 3.

TABLE 3. REFUSE AND COAL CONSUMED IN COFIRING AT COLUMBUS MUNICIPAL ELECTRIC PLANT (1977)

Month	Fuel, tons		Steam output, 10^6 pounds
	Coal	Refuse	
April	1,771	30	25.38
May	2,278	204	31.14
June	2,007	682	28.32
July	2,152	80	29.73
August	1,996	321	27.93
September	1,532	370	20.19
October	1,278	33	15.99

Refuse Combustion Observations

Fuel distribution was achieved by blowing refuse in through the two side ports. This action provided suspension burning during the trajectory of the refuse which fell 5 feet to the coal-covered grate. Coal was spread across the 20-foot width by five sets of paddles approximately 4 feet above the grate. Because the travelling grate moves away from the spreaders in this converted furnace, the refuse was added at the front of the grate near the spreaders. The heavy refuse particles which did not burn in suspension were consumed completely during the 30-minute time for the grate to travel to the rear.

The combustion of the refuse was complete for amounts of refuse up to 80 weight percent of the fuel with no unburned residue in the ash. For levels of refuse over 50 percent, however, to avoid pileup of refuse on the grates, careful attention was required to adjustment of the following:

(1) The refuse injection air

(2) The distributor plates in the spouts

(3) Overfire air beneath the refuse spouts

(4) Underfire air.

The use of refuse which has been shredded and magnetically separated but not air classified as a supplementary fuel in the spreader-stoker traveling-grate furnace has demonstrated that the melting of aluminum cans and other low-melting alloys may limit the amount of refuse utilized. If the underfire air is not or cannot be adequately maintained, these materials will melt and either react with the oxide scale on the grate or run through and solidify on the underside, thus disrupting grate travel. The seriousness of this problem depends on the amount of low-melting material in the refuse, and it could require specially designed grates and underfire air supply to handle refuse that has not been air classified.

SECTION 6

RESULTS OF FIRESIDE CORROSIVITY AND STACK EMISSION STUDIES

In addition to the many short experiments on the handling and furnace feeding of the shredded municipal waste that were required to optimize the system, 14 corrosion probes were run on this program, as shown in Table 4.

TABLE 4. FUELS AND STEAMING RATES FOR THE CORROSION PROBE EXPOSURES

Probe Nos.	Duration, hr	Coal, wt % S	Refuse		Average steam flow, lb/hr (1000 kg/hr)
			Wt %	Btu %	
27 & 28	8	3.3	0	–	120,000 (54.5)
29 & 30	8	0.9	0	–	94,000 (42.7)
31	8	2.6	28	17	104,000 (47.3)
32	2.5	2.6	50	30	(100,000) (45.5)
33	8	5.2	27	17	118,000 (53.6)
34	8	5.2	0	–	118,000 (53.6)
35	8	3.8	36	23	74,000 (33.6)
36	8	3.3	42	28	93,000 (42.3)
37	8	3.3	74	58	50,000 (22.8)
38	708	2.2–3.5	22	13	66,300 (42.3)
39	79	2.3	36	21	73,600 (33.5)
40	75	0.9	16	9	74,200 (33.7)

The baseline runs with the three coals of different sulfur content were conducted for 8-hour periods. For Probes 27–30, two probes were exposed at the same time in different temperature zones of the boiler, but with the very high sulfur coal (Probe 34) only a single run was made. Before the permanent refuse handling system was installed, manpower requirements of the system limited the runs to 8 hours.

The St. Louis refuse was used for Runs 31 and 32. The latter run was aborted after only 2.5 hours of probe exposure because of a breakdown of the agricultural equipment feed system. All of the other runs were carried out with the Columbus refuse. Probes 37–40 were done with the permanent refuse handling system, while all prior refuse experiments utilized the agricultural equipment.

FUEL ANALYSES

The coals, the St. Louis refuse, the Columbus refuse, and the refuse-coal mix (Probe 31) that were used on the program were analyzed for heating value and chemical composition. The data are presented in Table 5. The heating values, which were measured by standard calorimetry techniques, showed a range from 24,690–28,120 joules/gram (10,625 to 12,100 Btu/lb) for the high-sulfur coals, and the low-sulfur coal had an appreciably higher value of 31,025 joules/gram (13,350 Btu/lb). The refuse heating values were typical for such material. The nonmetal elements, the water, and the ash were determined by standard combustion train and wet chemical methods. The metal content was determined by optical emission spectroscopy. The ultimate analyses for the coal and refuse were made in duplicate, and the tabulated results are an average. The metal content values were from a single determination. The refuse and coal samples were obtained by accumulating small batches taken hourly from the streams going to the boiler. One such sample for each coal, the St. Louis refuse, and the Columbus refuse was then analyzed. Standard ASTM techniques were used to obtain representative portions of each sample for analysis.

The percentage compositions for the major elements were typical of coal compositions, and the refuse analysis showed the effect of the magnetic separation and air classifying treatments which it received. The heavy metal content of the refuse was very small, as it consisted primarily of paper products, wood chips, and plastic.

As expected, the chlorine content of the refuse was greater than that of any of the coals. A relatively low value for chlorine was found in the sample of the Probe 31 refuse-coal mix which was analyzed. The discrepancy between the refuse-coal ratio on a weight basis (28 percent) and the relative chlorine values reflects the difficulty in getting representative sampling of the refuse.

The Columbus refuse had a heating value about 300 Btu/lb greater than the St. Louis refuse. The air-classified Columbus sample had a relatively high ash content of 26.5 percent, mainly as a result of some accumulation of glass and sand particles at the sampling point in the furnace feed pipe. The sulfur and chlorine contents of the Columbus refuse were typical of municipal refuse. The amounts of metals in the refuse fed to the furnace were about the same as those found for the St. Louis refuse, and consisted primarily of aluminum.

The refuse samples also were sorted into categories for comparison of their contents. The results are shown in Table 6. The St. Louis refuse sample had an unusually high paper content. On the other hand, the Columbus refuse, which had gone through the air classifier in the temporary handling system, had a high content of glass and sand, as pointed out above. From the viewpoint of corrosion it should be noted that in all three samples the polyvinyl chloride content of the refuse was slightly greater than the 0.5 percent which is now considered the average in the U.S. Pieces of aluminum foil accounted for the relatively high metal content of the air-classified St. Louis refuse.

The content of metals in the refuse which form alkaline oxides, such as sodium, magnesium, and calcium, was greater than found in any of the coals. These elements in the refuse should assist in removal of the sulfur oxides formed during combustion of the coal. When larger amounts of refuse are used in the combined firing, the effects of these alkaline components should be maximized. Of the trace elements, only lead and manganese appeared in significantly greater amount in the refuse than in the coals.

TABLE 5. FUEL ANALYSIS

	High-sulfur coal Probes 27/28	Low-sulfur coal Probes 29/30/40	High-sulfur coal Probes 31/32	St. Louis refuse Probe 32	St. Louis refuse + coal Probe 31	High-sulfur coal Probes 33/34	Columbus refuse Probe 33	High-sulfur coal Probes 35/37/38	High-sulfur coal Probe 36	High-sulfur coal Probe 39
Btu/lb, gross:	12,100	13,350	11,920	5,550[a]	10,150	10,625	5,875[a]	11,580	11,850	12,070
Material	Composition, weight percent									
S	3.29	0.93	2.58	0.05	2.36	5.24	0.30	3.16	2.99	2.32
Cl	0.02	0.15	0.03	0.9	0.04	0.014	0.64	0.03		
C	61.64	74.53	61.69	41.5	61.0	57.8	42.8	64.0		
H	4.45	5.37	5.28	5.7	5.6	5.31	6.33	4.91		
H_2O	6.48	1.81	6.74	28.1	7.1	4.63	26.6	5.86	3.6	3.5
Ash	15.2	10.9	13.1	19.2	18.4	19.3	26.5	12.0	10.25	10.1
Si	4.5	4.5	2	5.8	3	3-5	6.6	1-2		
Fe	2	0.5	2	0.6	2.4	5-10	0.8	1-2		
Al	2	2	1.5	0.8	1.4	1-3	0.7	1.0		
Ca	1	0.03	0.1	2.4	0.2	0.07	4.0	0.2		
Mg	0.1	0.06	0.05	0.2	0.06	0.03	0.3	0.05		
Na	<0.1	<0.1	0.1	1.0	0.8	0.1	1.1	0.2		
K	0.3	0.3	0.5	0.3	0.3	0.3	0.8	0.2		
Ti	0.07	0.1	0.1	0.06	0.1	0.05	0.05	0.03		
Pb	<0.01	<0.01	<0.003	0.04	<0.01	<0.03	0.05	<0.01		
Zn	<0.1	<0.1	<0.1	0.02	<0.1	<0.1	0.03	<0.1		
Sn	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	0.003	<0.01		
Mn	0.01	<0.01	0.003	0.04	0.006	0.003	0.03	0.01		
As	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.01	<0.1		
Ba	0.01	0.01	0.01	0.006	0.02	0.03	0.03	<0.01		
B	0.01	0.01	0.01	0.002	0.01	0.01	0.005	<0.01		
V	<0.01	<0.01	<0.003	<0.002	0.002	0.003	<0.002	<0.01		
Cr	<0.01	<0.01	<0.005	0.01	0.01	<0.003	0.008	<0.01		
Ni	<0.005	<0.005	<0.003	0.002	0.001	0.005	0.005	<0.01		

(a) Moisture-free value.

TABLE 6. COMPOSITION OF MUNICIPAL SHREDDED WASTE SAMPLES

Constituent	Weight percent in refuse		
	St. Louis[a]	Columbus	
		Sample 1[a]	Sample 2[b]
Paper	85.7	67.4	57.8
Textiles	1.1	4.1	3.9
Wood	0.8	2.8	3.6
Metal	2.0	0.6	1.2
Plastics:			
Polyethylene	0.9	2.1	3.0
Polystyrene	0.1	1.2	0.7
Polyvinyl chloride	0.9	0.6	0.8
Polyurethane	1.0	0.1	0.8
Cellophane	–	–	0.1
Composities	–	–	0.5
Glass	–	–	3.6
Glass and Sand	7.5	20.1	–
Sand	–	–	13.8
Building materials			
Gravel/plaster	–	–	10.2
Roofing	–	1.0	–
Total	100	100	100

(a) Air classified in addition to magnetic separation.
(b) Magnetic separation only.

During the Probe 35 run it was observed that there was a significant amount of grass clippings in the refuse. In order to estimate the effect of the grass, some clippings were analyzed for heating value and found to yield 16,220 joules/gram (6980 Btu/lb), which is higher than the value for the mixed refuse samples measured previously. Consequently, it can be deduced that the heating value of the refuse burned for the Probe 35 run was about 465 joules/gram (200 Btu/lb) greater than that of the other runs. It is of particular interest that the grass clippings were found to contain 1 percent chlorine and 0.3 percent sulfur. If this high chlorine value is typical of grass clippings, this component of refuse can be an important contributor to corrosion.

CORROSIVITY INVESTIGATIONS

The corrosivity of the combustion products was evaluated by inserting Battelle-designed air-cooled corrosion probes (Figure 14) in the furnace in the area of the superheat tubes. At this location the gas temperature varied from 593 C (1100 F) under low load conditions to 760 C (1400 F) for the higher loads. The air cooling maintained specimen temperatures of 260 to 510 C (500 to 950 F) as measured by thermocouples inserted in the wall section of several specimens along the probe. Eighteen specimens 2.54 x 3.17 x 3.81 cm (1 inch ID x 1.25 inch OD x 1.5 inch long), consisting of the alloys described in Table 7, were nested together with lapped joints and spring loaded to prevent leakage of air at the joints.

Corrosion rates were determined by weight loss measurements after removal of the reacted metal using inhibited 10 percent H_2SO_4 while the sample was made 6 volts cathodic to a carbon anode. The corrosion rate in mils per hour was calculated from the weight loss, assuming uniform attack around the specimen surface. Corrosion rates were plotted as functions of time, temperature, and percent refuse, and each point designated in the plots represents a single corrosion specimen. The corrosion rates in the cofiring environment for A106 carbon steel as a function of time are shown in Figure 15. The values for 100 percent refuse combustion were obtained from the previous exposures at the Miami County incinerator and are shown in Figure 16. With high-sulfur coal and up to 46 weight percent refuse, the initial rates for refuse alone were reduced by a factor of ten. As the exposure time increased, the rates for 100 percent refuse and coal plus refuse became closer, but the shapes of the curves indicate that for extended exposures the corrosivity of the 100 percent refuse combustion environment will be about 5 to 10 times that of the high-sulfur coal with refuse.

The initial (8-hour) corrosion rates observed for the A106 carbon steel are presented in Figure 17 as a function of temperature. The rates for the cofiring of refuse and coal were essentially the same as those for coal alone, increasing slightly at 74 weight percent refuse. The highest corrosion rates occurred with the 5 percent sulfur coal alone and were the result of sulfide attack on the steel. The rates found with bulk refuse burning at the incinerator were greater by about a factor of ten, as shown by the dashed line in the upper part of Figure 17.

The 8-hour corrosion rate for carbon steel did not change significantly as the amount of refuse in the cofiring mixture was increased. As shown in Figure 18, the rates at both 260 and 482 C (500 and 900 F) were essentially those for coal alone up to 74 weight percent refuse. Somewhere above 75 percent refuse the rates must increase rapidly as indicated by the broken lines.

The corrosion rates for 8-hour exposures of the various stainless steels are shown in Figure 19. The lower plot shows the data for the most corrosion-resistant alloys, which proved to be Type 310 stainless steel and JS700. The center plot presents the results for Types 316, 347, and 446 stainless steels, which proved to be less resistant to the refuse-coal combustion environment. The upper plot shows that the rates with 100 percent refuse were 10 to 30 times greater than those with the mixed fuel. Essentially no temperature dependence was found for the corrosion encountered with 100 percent refuse combustion. The corrosion data for the various alloys interpolated to uniform temperatures are summarized in Table 8.

When the exposure time was lengthened to 80 hours, the corrosion rates for all of the steels were reduced as a result of the protective oxide layers which developed on the metal surfaces. The corrosion data for these exposures are given in Figure 20. As found in the 8-hour exposures, the Type 310

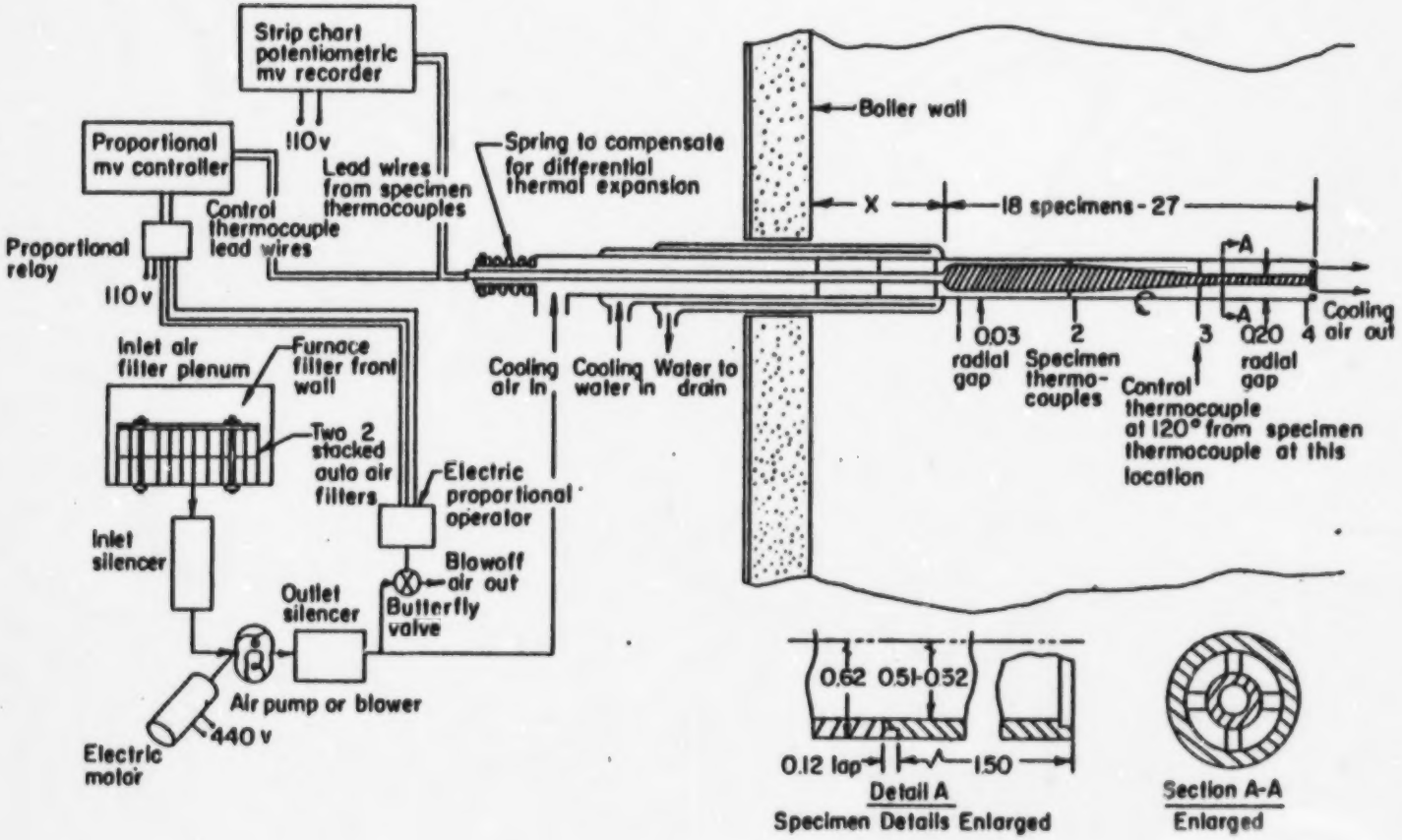

Figure 14. Schematic diagram of corrosion probe and control apparatus.

TABLE 7. COMPOSITION OF ALLOYS

Alloy	Nominal weight percent								
	Cr	Ni	Mn	Mo	Si	P	S	C	Others
A106	–	–	0.76	–	0.23	0.02	0.02	0.20	–
T11	1.25	–	0.40	0.50	0.75	–	–	0.15	–
P5	4.98	–	0.44	0.52	0.41	0.01	0.02	0.11	–
P9	8.80	–	0.40	1.00	0.70	0.03	0.03	0.15	–
405	12.82	0.28	0.53	–	0.50	0.02	0.02	0.06	0.20 Al
446	26.50	0.50	1.50	–	0.75	–	–	0.20	–
316	17.00	12.50	–	2.50	0.75	–	–	0.03	2.00 Co
310	25.00	20.50	2.00	–	0.75	–	–	0.15	–
347	17.70	11.70	1.40	–	0.70	0.04	0.03	0.08	0.80 Cb
JS700	21.00	25.00	1.70	4.50	0.50	–	–	0.03	0.30 Cb

stainless steel had the lowest corrosion rate, followed by the Types 316 and 347 stainless steels. The P9 alloy had a slightly higher rate, and the scatter in the data for the P9 specimens is attributed to the tendency of this alloy to undergo spalling of the oxide film. This effect would result in some inconsistencies of weight loss among the samples. Although the corrosion rate for A106 carbon steel was significantly lower than that for 8-hour exposures, it was still about a factor of 10 greater than that for the stainless steels.

The interpolated values for the long-term corrosion rates are given in Table 9, which includes data for the 708-hour corrosion probe exposure. As shown in the table, the corrosion rates generally decreased further with the longer time to where they have probably leveled off and would not decrease significantly with additional exposure. Type 310 stainless steel, which already had a very low corrosion rate for the 79-hour exposure, incurred the same rate at 260 and 370 C (500 and 700 F) in the 708-hour exposure with a decrease at 482 C (900 F). At a metal temperature of 260 C (500 F) the A106 steel also had the same rate for the two exposure times. It should be noted that when 1 percent sulfur coal was burned with only 16 weight percent refuse (Probe 40), the corrosion rate of A106 stell was higher. This result indicates that the low-sulfur coal was not adequate to afford protection against even this small percentage of refuse.

The total metal wastage averaged for all the specimens of each material that occurred as a function of exposure time to the high-sulfur coal and refuse is shown in Figure 21. The low alloy P9 steel and the stainless steels are much more resistant to the refuse-coal environment than is the A106 carbon steel. However, except for the Type 310 stainless steel, the corrosion curves do not appear to have leveled off completely, and a slight increase with time can still be anticipated. Nevertheless, even at the high rate of 2.5 mils in 700 hours for the A106 steel, a boiler tube life of 6 years can be projected on the basis of 180 mils wastage from a 250 mil wall thickness. The rate will obviously decrease further with time, so the 6 years is a conservative figure. This rate would only have to decrease by 1/12 each 700 hours the first year and then remain essentially constant at 8–9 mils/yr to provide the 20-year life normally expected for tubes in a coal-fired boiler.

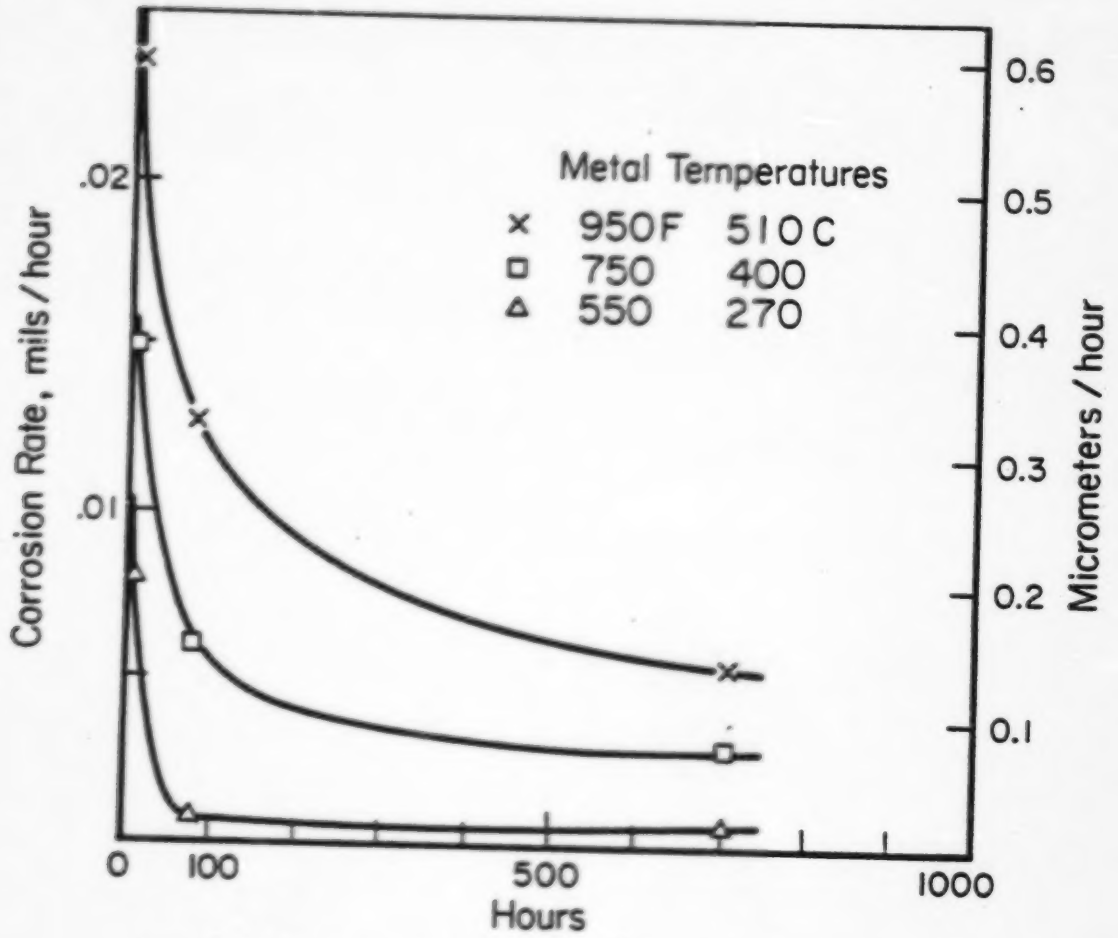

Figure 15. Corrosion rates versus exposure time for A106 carbon steel during cofiring of refuse and high-sulfur coal.

PROBE DEPOSIT AND SCALE ANALYSIS

During the exposure of corrosion probes in the combustion product environment, the probes become coated with fly ash and particulates that condense on the cooler specimen surfaces. Reaction between these deposits and the substrate depends upon several factors, such as (1) the type of oxide scale on the metal substrates, (2) the composition of the deposit, (3) thermal conductivity and stability of the deposit, and (4) the duration of the exposure. The interface reaction products are defined as the scale layer which has been identified as iron oxides and sulfide except when the fuel is 100 percent refuse. In this case, the scale consists of iron oxides over a layer of iron chloride, resulting in very high corrosion rates. To characterize the deposit as a function of the refuse content of the fuel, optical emission spectroscopic and wet chemical analyses were conducted on the deposit taken from

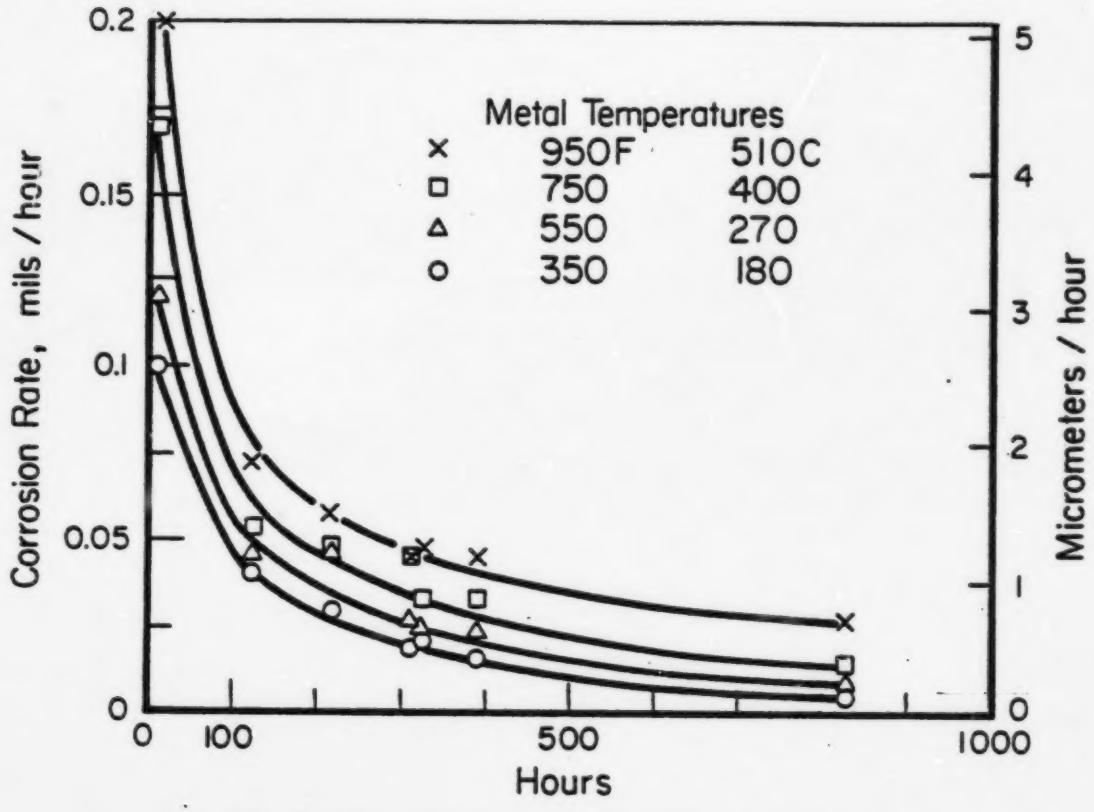

Figure 16. Corrosion rates versus time for A106 carbon steel exposed to mass burning of refuse.

several specimens used in the corrosivity evaluations. A comparison of the results for coal, coal plus refuse, and 100 percent refuse (Table 10) shows the following:

(1) Little change occurs in metal content from coal alone to coal with up to 74 weight percent refuse. Na, Ca, Zn, and Pb increase as the amount of refuse increases.

(2) The amounts of elements Na, Mg, K, Zn, and Pb are higher while the amounts of Si, Al, and Ti are lower in deposits from 100 percent refuse burning than in those from coal burning.

(3) Very high chlorine contents are found in deposits from refuse burning, which decrease to negligible amounts in the deposits from coal or from coal with up to 74 weight percent refuse.

(4) The sulfur content of the deposits varies approximately in proportion to that in the fuel except in the case of refuse burning, where the alkali metal oxides and chlorides are converted to sulfates in the deposits.

(5) The deposits from refuse burning are much thicker than those with coal or coal plus up to 74 weight percent refuse fuels.

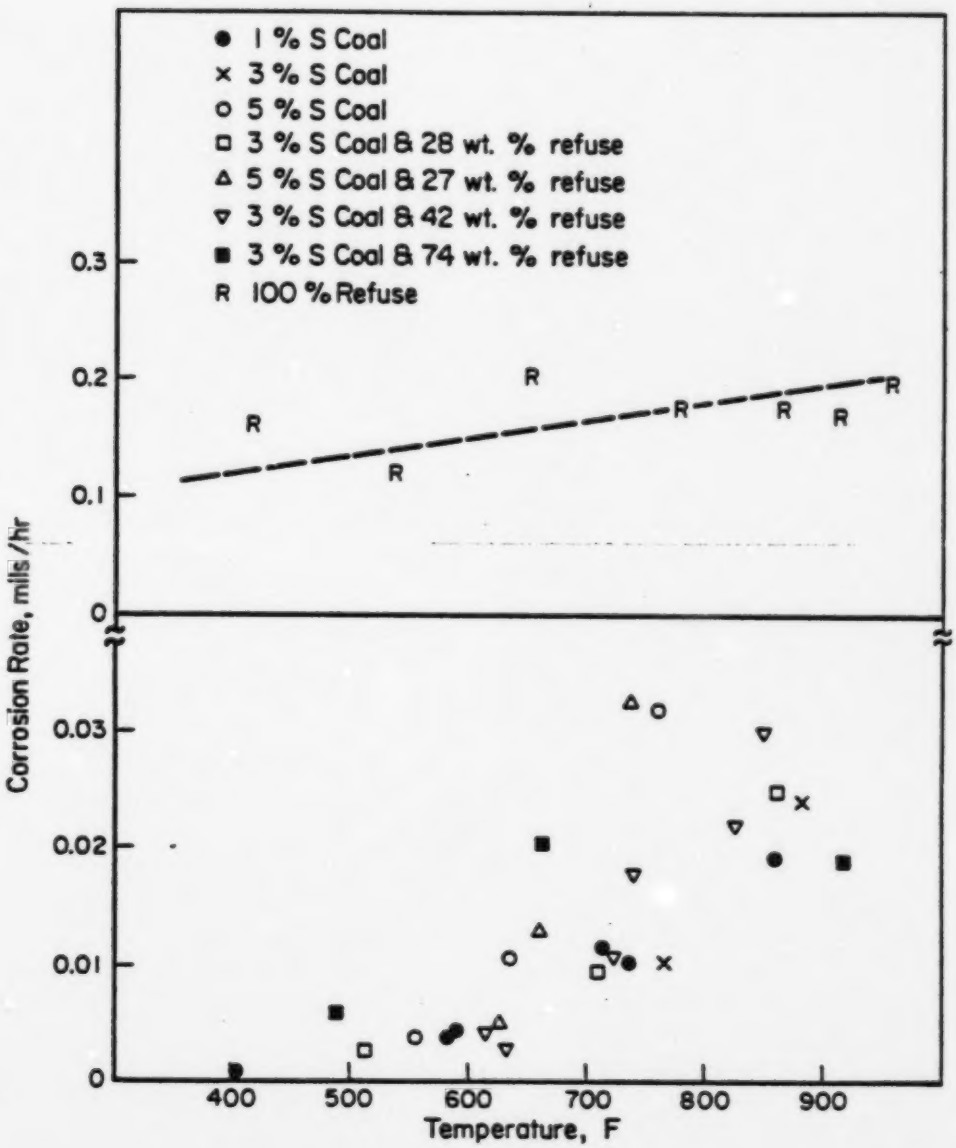

Figure 17. Initial corrosion rates of A106 carbon steel versus metal temperature.

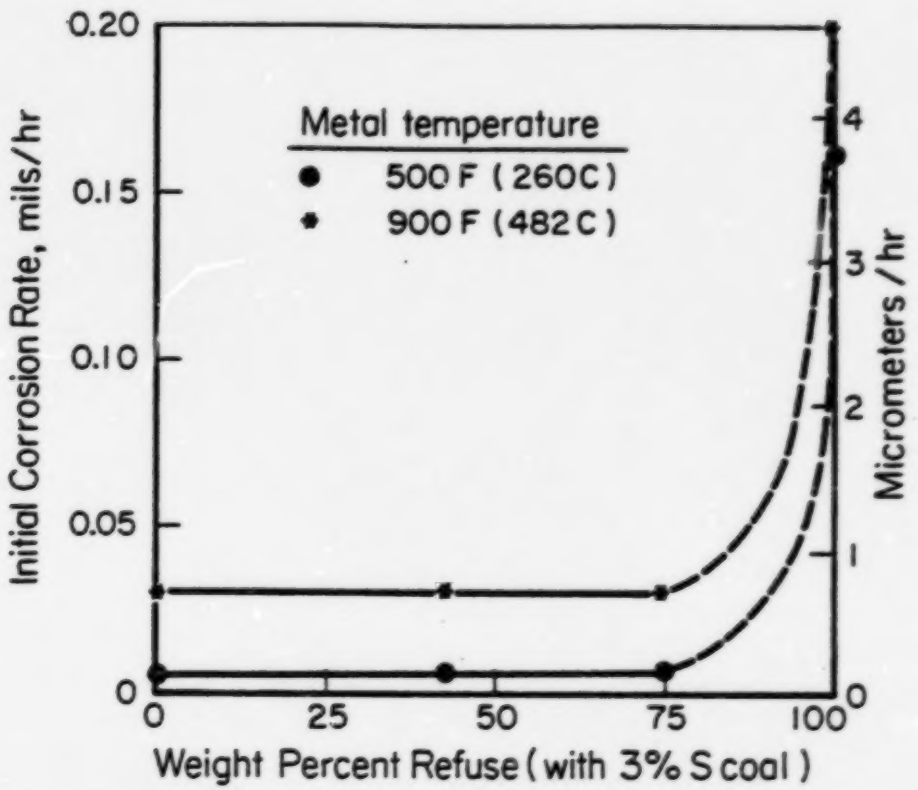

Figure 18. Initial corrosion rates for carbon steel as a function of refuse content of fuel mixture.

The reactions at the deposit-to-metal interface (scale layer) are of primary importance in understanding the mechanism of metal wastage. This scale layer is usually quite thin and consists of several compounds which form at specific locations in the scale layer. The compounds identified in the scale layer on probe specimens exposed to the environments produced by burning of the various fuels are presented in Table 11. The major difference among the various scale layer samples was the presence of iron chloride in the scale layer formed by burning 100 percent refuse, whereas iron sulfides were present when coal or coal with up to 42 weight percent refuse was burned. The iron oxides were present as expected on all specimens but were separated from the metal substrate by the iron chloride layer in the scales formed by burning 100 percent refuse. On the other hand, sulfide formed by burning coal appeared to be mixed in the oxide scale, suggesting that perhaps the iron sulfide was a deposit rather than a reaction product.

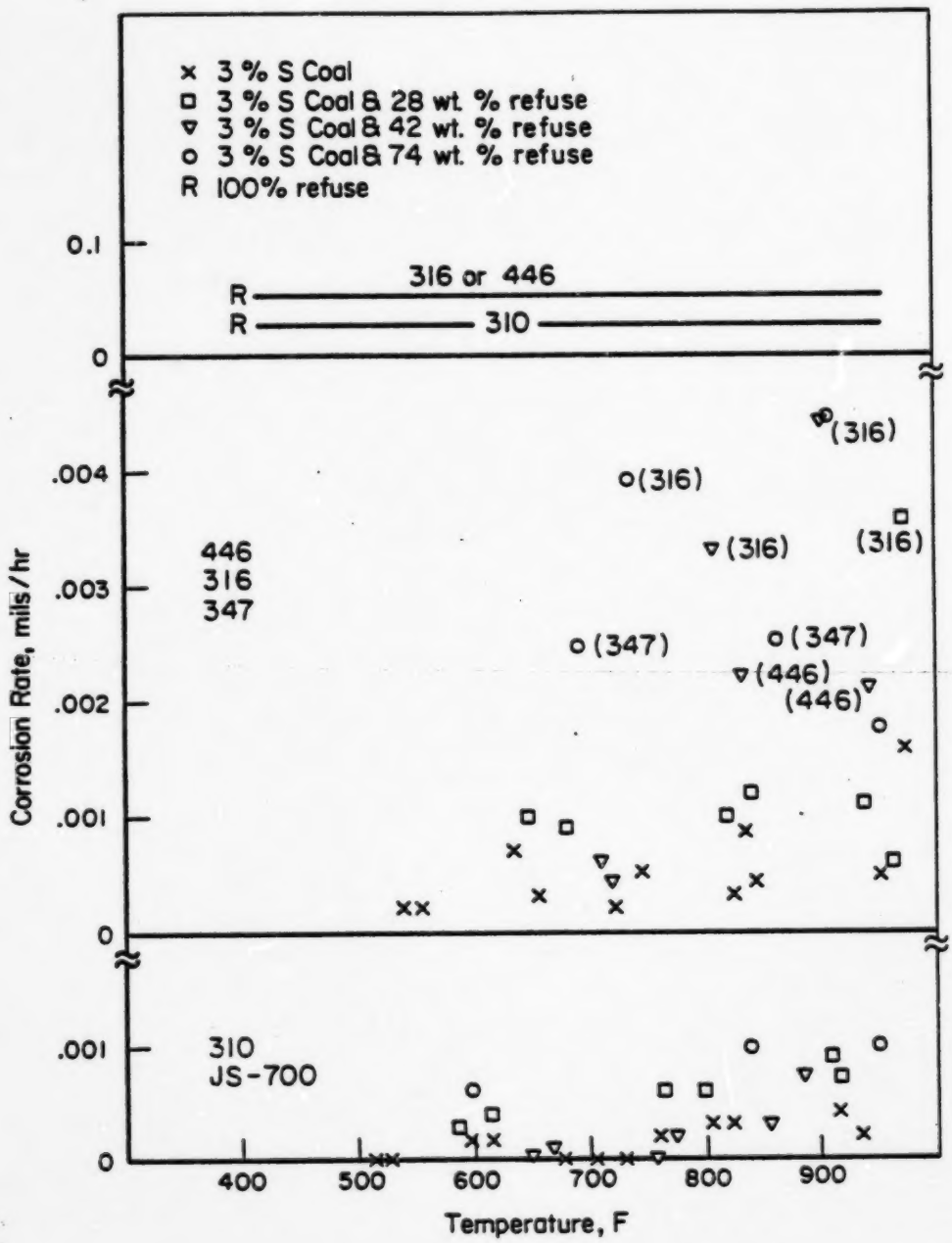

Figure 19. Initial corrosion rates of stainless steels versus metal temperature.

TABLE 8. INITIAL CORROSION RATES FOR VARIOUS ALLOYS AS A FUNCTION OF METAL TEMPERATURE AND FUEL (MILS PER HOUR)

Alloy	Metal temp. F	Probe 30 1% coal	Probe 28 3% S coal	Probe 34 5% S coal	Probe 31 3% S coal 28 wt % refuse	Probe 33 5% S coal 27 wt % refuse	Probe 35 3% S coal 36 wt % refuse	Probe 36 3% S coal 42 wt % refuse	Probe 37 3% S coal 74 wt % refuse	100% refuse[a]
A106	500	0.004	0.005	0.002	0.002	0.002	0.003	0.001	0.006	0.16
	700	0.008	0.007	0.020	0.010	0.021	0.008	0.012	0.013	0.18
	900	0.022	0.027	0.063	0.030	0.068	0.031	0.035	0.020	0.20
T11	500	0.005	0.005	0.002	0.004	0.003	0.002	0.002	–	0.10
	700	0.006	0.007	0.013	0.005	0.018	0.006	0.005	–	0.12
	900	0.013	0.022	0.034	0.022	0.037	0.020	0.020	–	0.18
316	500	0.003	Nil	Nil	Nil	Nil	Nil	Nil	0.004	–
	700	0.005	Nil	0.001	0.001	0.001	Nil	Nil	0.004	0.056
	900	0.006	0.001	0.002	0.001	0.002	0.004	0.002	0.004	0.056
446	500	0.003	Nil	Nil	0.001	0.001	–	–	–	–
	700	0.007	Nil	0.0005	0.001	0.001	–	–	–	0.050
	900	0.001	0.001	0.001	0.001	–	–	–	–	0.050
310	500	Nil	Nil	Nil	Nil	Nil	Nil	Nil	0.0005	–
	700	Nil	Nil	Nil	0.0005	0.0005	Nil	Nil	0.0007	0.032
	900	0.0001	0.0005	0.0005	0.0005	0.001	0.0005	0.001	0.001	0.032
JS700	500	Nil	Nil	–	Nil	–	–	–	–	–
	700	Nil	Nil	–	0.0005	–	–	–	–	–
	900	0.0006	Nil	–	0.0005	–	–	–	–	–
405	500	–	–	0.001	–	0.001	Nil	Nil	–	–
	700	–	–	0.003	–	0.009	0.002	0.006	–	–
	900	–	–	0.008	–	0.010	0.010	0.012	–	–
P5	500	–	–	–	–	–	0.003	–	–	–
	700	–	–	–	–	–	0.008	0.012	–	–
	900	–	–	–	–	–	0.020	0.013	–	–
P9	500	–	–	–	–	–	–	–	0.009	–
	700	–	–	–	–	–	–	–	0.010	–
	900	–	–	–	–	–	–	–	0.012	–
347	500	–	–	–	–	–	–	–	0.002	–
	700	–	–	–	–	–	–	–	0.002	–
	900	–	–	–	–	–	–	–	0.002	–

(a) Data obtained from incinerator under EPA Research Grant No. 800055.

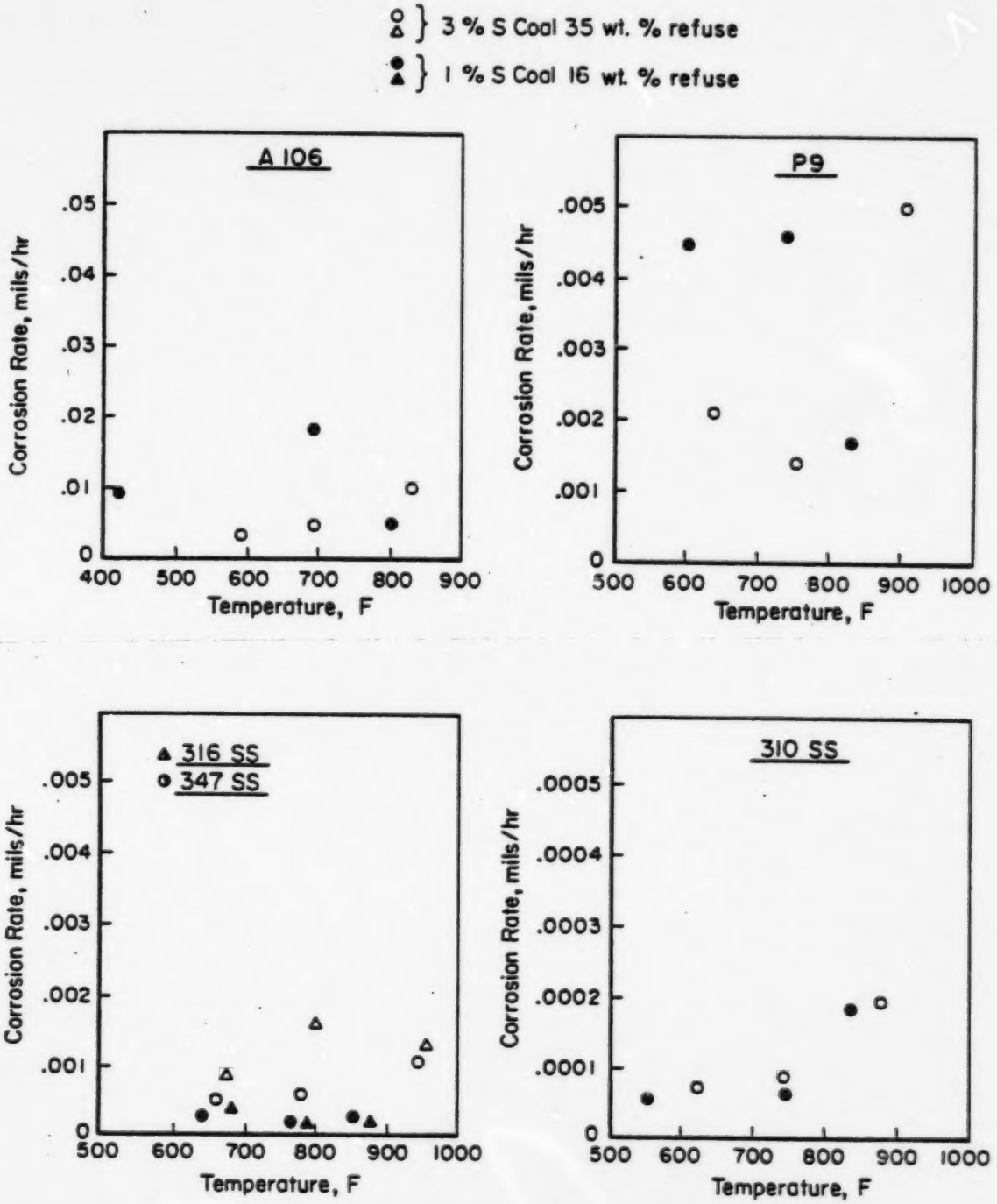

Figure 20. Corrosion rates versus temperature for 80-hour exposures with refuse and coal.

TABLE 9. LONG-TERM CORROSION RATES FOR VARIOUS ALLOYS AS A FUNCTION OF METAL TEMPERATURE AND FUEL (MILS PER HOUR)

Alloy	Metal temp, F	Probe 40 75 hours 1% S coal 16 wt % refuse	Probe 39 79 hours 2.3% S coal 35 wt % refuse	Probe 38 708 hours 3% S coal 22 wt % refuse
A106	500	0.005	0.001	0.001
	700	0.012	0.005	0.003
	900	0.019	0.010	0.005
316	500	0.0001	0.0009	0.0002
	700	0.0002	0.001	0.0004
	900	0.0002	0.001	0.0008
310	500	Nil	Nil	Nil
	700	0.0001	0.0001	0.0001
	900	0.0002	0.0002	0.0001
P9	500	0.004	0.001	0.0008
	700	0.005	0.002	0.0010
	900	0.001	0.004	0.0012
347	500	Nil	0.0002	0.0001
	700	0.0002	0.0006	0.0003
	900	0.0004	0.0010	0.0008

STACK EMISSION ANALYSES

The stack emissions were measured by standard EPA techniques for sulfur oxides, nitrogen oxides, and particulates. HCl concentrations were determined by measuring the chloride content of the impingers in the sulfur oxide train. Oxygen and the CO_2 were measured by Orsat analysis of a bag sample of the stack gases accumulated during the run. The CO and organic compounds were determined by mass spectrometer analysis of grab samples taken in evacuated bulbs. The polynuclear hydrocarbons were collected in the packed-column condenser system which has been developed at Battelle under EPA sponsorship. The samples for particle-size distribution were collected using in-stack thimbles. The stack emisssion data for all of the runs are summarized in Table 12.

The concentrations of SO_2 in the stack gases are plotted as a function of the sulfur content of the coal in Figure 22. The SO_2 concentration did not increase linearly with the sulfur content of the coal when it was burned alone, probably because the burnout of the sulfur was less complete at the higher sulfur levels. The broken line extrapolation indicates the expected level of SO_2 from the 5.2 percent sulfur coal. The SO_2 concentration was reduced as a result of the dilution of the high-sulfur coal with the low-sulfur (0.25 weight percent) refuse. In addition, the alkaline components of the refuse are capable of reducing the SO_2 further. The three lowest points in Figure 22 in which 36, 42, and 50

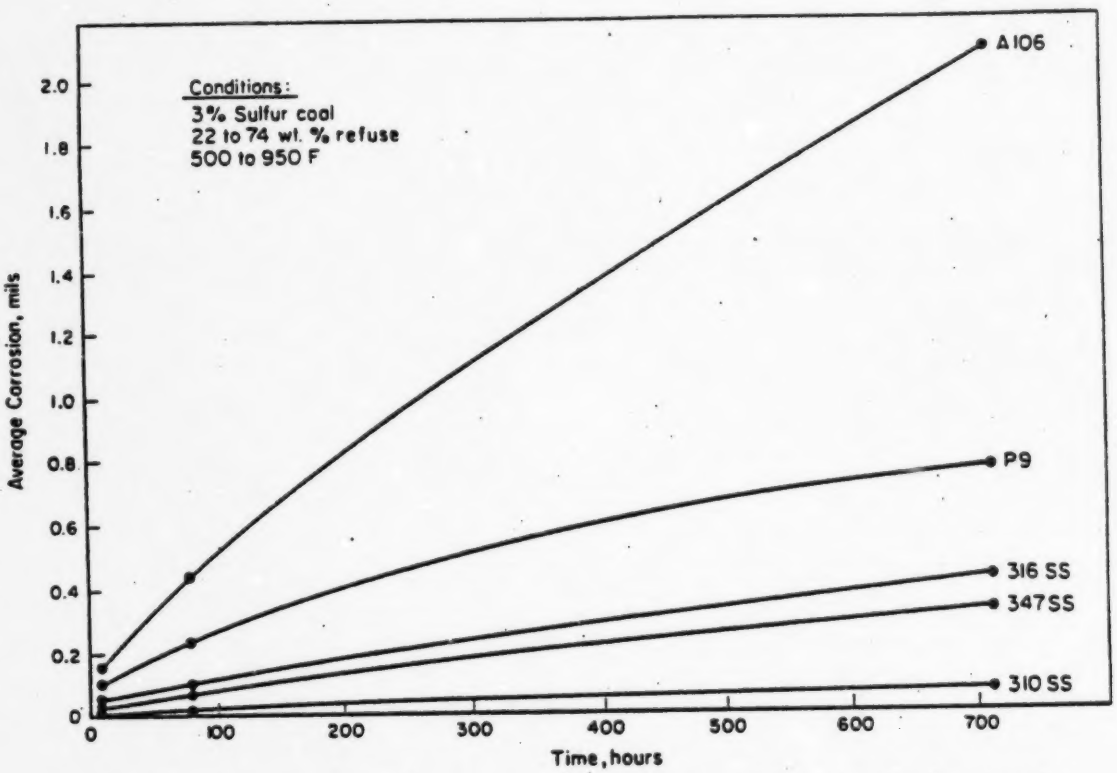

Figure 21. Total metal wastage as a function of time for various steels exposed to cofiring of refuse and high-sulfur coal.

weight percent refuse was burned correspond to SO_2 reductions of 53, 52, and 61 percent respectively. Hence, in these runs the alkaline refuse components were effective. However, in the other two they were not effective.

These results indicate the importance of the combustion conditions on the efficiency of SO_2 reduction. Typical municipal refuse contains about 8.2 g/kg (80 lb/ton) of Na, K, Ca, and Mg which are all capable of forming metal oxides and then sulfates with SO_2 and oxygen. These base-forming elements are sufficient to react with all of the sulfur in a ton of 3 percent sulfur coal, provided the necessary conditions of residence time, contact, and diffusion rates could be met. Obviously, not all of the SO_2 will be reacted in this fashion, but it should be possible to obtain some SO_2 removal with the basic elements from refuse.

Of the other gaseous components in the stack gases, none is present in amounts that would constitute a problem. Small amounts of HCl were found with slight increases over those from the coal alone. Nitrogen oxide concentrations appear to reflect combustion temperatures rather than any direct effect of refuse burning. Gaseous organic compounds have not been present in significant amounts. Only in run 36 was there any significant amount of carbon monoxide in the stack gases. This run was made during the time when the agricultural equipment was being used to feed the

TABLE 10. COMPOSITION OF DEPOSITS ON CORROSION PROBES

Probe run	30	28	34	40	38	31	39	35	37	21[a]
Fuel mixture	1% S coal	3% S coal	5% S coal	1% S coal + 16 wt % refuse	3% S coal + 22 wt % refuse	3% S coal + 27 wt % refuse	3% S coal + 35 wt % refuse	3% S coal + 36 wt % refuse	3% S coal + 74 wt % refuse	100% refuse
Elements	Weight percent									
B	<0.1	0.1	0.3	0.01	0.03	0.3	0.03	–	0.03	<0.1
Na	0.3	0.5	0.3	1–2	1–2	1.0	1.0	1.0	2–3	2.0
Mg	0.3	0.5	0.2	0.5	0.5	0.3	0.5	0.4	1.0	0.7
Al	5–10	5–10	4–7	5–10	5–7	5–10	5–7	3–5	4–6	4–7
Si	15–25	10–15	5–10	10–20	10–15	10–20	5–10	5–10	10–15	3–7
K	2.0	3.0	1–2	3–5	3–5	1.0	2–3	1.0	2–3	2–4
Ca	1.0	2–4	3–5	1–2	3–5	2–4	2–4	3–5	5–10	4–10
Ti	0.8	0.5	0.3	0.2	0.2	0.4	0.3	0.2	1–2	0.3
V	–	–	0.03	0.01	0.01	0.01	0.01	0.01	0.01	–
Cr	<0.1	<0.1	0.03	0.03	0.04	0.03	0.1	0.2	0.03	<0.1
Mn	<0.1	<0.1	0.02	0.03	0.05	0.07	0.1	0.08	0.2	0.2
Fe	4–8	15–25	15–25	5–10	5–10	15–25	8–12	15–25	5–10	15–25
Co	–	–	0.01	<0.01	<0.01	0.01	<0.01	0.01	–	–
Ni	<0.1	<0.1	0.01	0.02	0.05	0.02	0.07	0.1	0.03	–
Cu	0.2	<0.1	0.03	0.04	0.03	0.04	–	0.02	–	<0.1
Zn	<0.1	0.1	0.2	1–3	2–4	0.4	2–4	0.5	3–5	3.0
As	<0.1	0.2	0.3	–	0.3	0.3	–	–	–	–
Sr	–	–	0.06	0.04	0.03	0.03	0.03	0.03	0.03	–
Zr	–	–	0.01	0.01	0.01	0.01	–	0.01	0.01	–
Sn	<0.1	<0.1	0.01	0.05	0.2	0.04	0.1	0.03	0.3	0.1
Sb	0.1	<0.1	–	–	0.02	–	–	–	0.03	<0.1
Ba	0.1	<0.1	0.08	0.07	0.03	0.04	0.03	0.05	0.1	–
Pb	0.1	0.1	0.2	1–2	1.0	0.4	1–2	0.4	1–2	0.4
Cl[b]	0.02–0.1	Nil–0.04	0.01–0.02	0.45	0.04	Nil–0.11	0.03	0.01–0.03	0.03	2–8
S[b]	1.2–1.6	6–8	2.6–3.4	5.8	6.0	2.7–3.1	9.0	2–4	8.1	3–5

(a) Data from probe exposed in incinerator.
(b) Wet chemical analyses.

TABLE 11. PHASES IN SCALE LAYER AS A FUNCTION OF FUEL

Probe No.	Fuel	Phases
28	3 percent S coal	$Fe_3O_4 + Fe_2O_3 + FeS + CaSO_4$
34	5 percent S coal	$Fe_3O_4 + FeS + Fe_2O_3 + SiO_2$
35	5 percent S coal + 45 wt % refuse	$Fe_3O_4 + Fe_2O_3 + \alpha FeOOH + FeS + SiO_2$
21	100 percent refuse	$FeCl_2 \cdot 2H_2O + FeCl_2 \cdot 4H_2O + \beta FeOOH + Fe_3O_4$

refuse. It was difficult to obtain uniform feed at all times with this equipment, and occasional pileups of refuse on the grate occurred. It is likely that this condition resulted in the higher CO concentration.

Particulate emissions are difficult to evaluate because two of the baseline runs were made before sections of the cyclone separators were replaced. It should be noted that the cyclones are the only emission controls on this boiler, so it would be difficult to make any comparison with data obtained on a unit having some other type of gas cleanup system.

The opacity of the stack emissions with refuse burning was no worse than that when coal was burned alone.

The particle size distribution measured by the Coulter counter for 36 weight percent refuse is shown in Figure 23 with those from runs with high-sulfur coal alone and combined with 27 weight percent refuse. In the run with more refuse there were more large particles. None of the particles collected was below 1 micrometer in size, and a small percentage was larger than 100 micrometers. These results were obtained during the time the agricultural equipment was in use for refuse feeding and could have been influenced by difficulties in getting uniform distribution on the grates.

FURNACE PARTICULATES

Because the cyclones were the only emission controls, it was decided that useful information could be obtained by measuring the total particulate burden leaving the boiler with and without refuse. In this way the amount of control required can be determined.

Consequently, particulate measurements were made at the economizer outlet, just ahead of the cyclones. The data were taken across the duct, using EPA Method 5, with coal alone and with coal plus refuse. The results showed that under the stoker conditions used, the addition of refuse to the coal could bring about either a slight increase or decrease in the particulate loading (Table 13).

TABLE 12. STACK EMISSIONS

	5.2 wt % S coal	27 wt % refuse + 5.2 wt % S coal	3.2 wt % S coal	36 wt % refuse + 3.2 wt % S coal	42 wt % refuse + 3.2 wt % S coal	42 wt % refuse + 3.2 wt % S coal	50 wt % refuse + 2.6 wt % S coal[c]	50 wt % refuse + 2.3 wt % S coal	1 wt % S coal
Probe run	34	33	27/28	35	36	No probe	32	37	29/30
Steam flow, lb/hr	118,000	118,000	120,000	74,000	93,000	90,000	100,000	50,000	94,000
SO_2, ppm	3,120	3,090	2,340	1,190	1,615	960	400[d]	760	720
SO_3, ppm	68	61	12	20	27	2	ND	60	5
HCl, ppm	5	26	14	36	45	97	ND	103	45
NO_x, ppm	48	27	210	127	214	94	180	ND	162
O_2, percent	11.0	11.1	10.4	9.1	12.0	12.5	10.5	10.0	10.7
CO_2, percent	8.5	8.6	9.6	10.5	7.7	6.0	8.5	7.0	10.5
CO, percent	0.004	0.021	<0.1	0.022	0.39	<0.1	0.20	<0.1	0.02
H_2O, percent	10.9	10.1	9.4	8.6	8.3	7.2	9.2	ND	5.8
CH_4, ppm	Nil	18	ND[a]	2	2	ND	19	ND	<1
C_2H_4, ppm	0.04	3	ND	0.2	0.3	ND	3	ND	<1
Vinyl chloride, ppm	Nil	Nil	ND	Nil	Nil	ND	Nil	ND	ND
Particulate, gr/scf	0.37	0.65	1.20[b]	0.45	0.52	1.14	ND	ND	1.42[b]

(a) ND = not determined.
(b) Cyclone separators defective.
(c) Analysis of grab sample.
(d) Mass spectrometer data – low in presence of moisture.

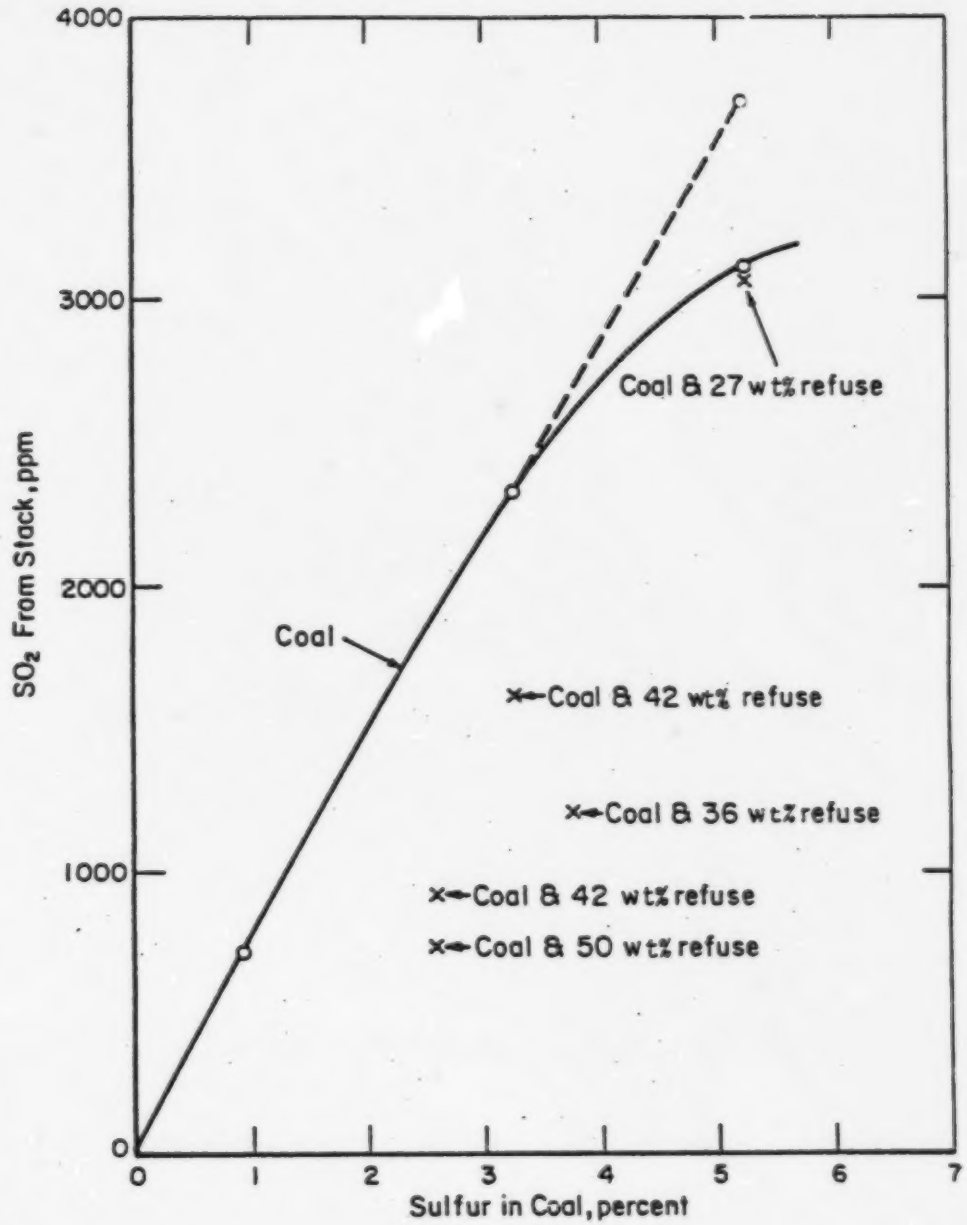

Figure 22. SO_2 content of stack emissions.

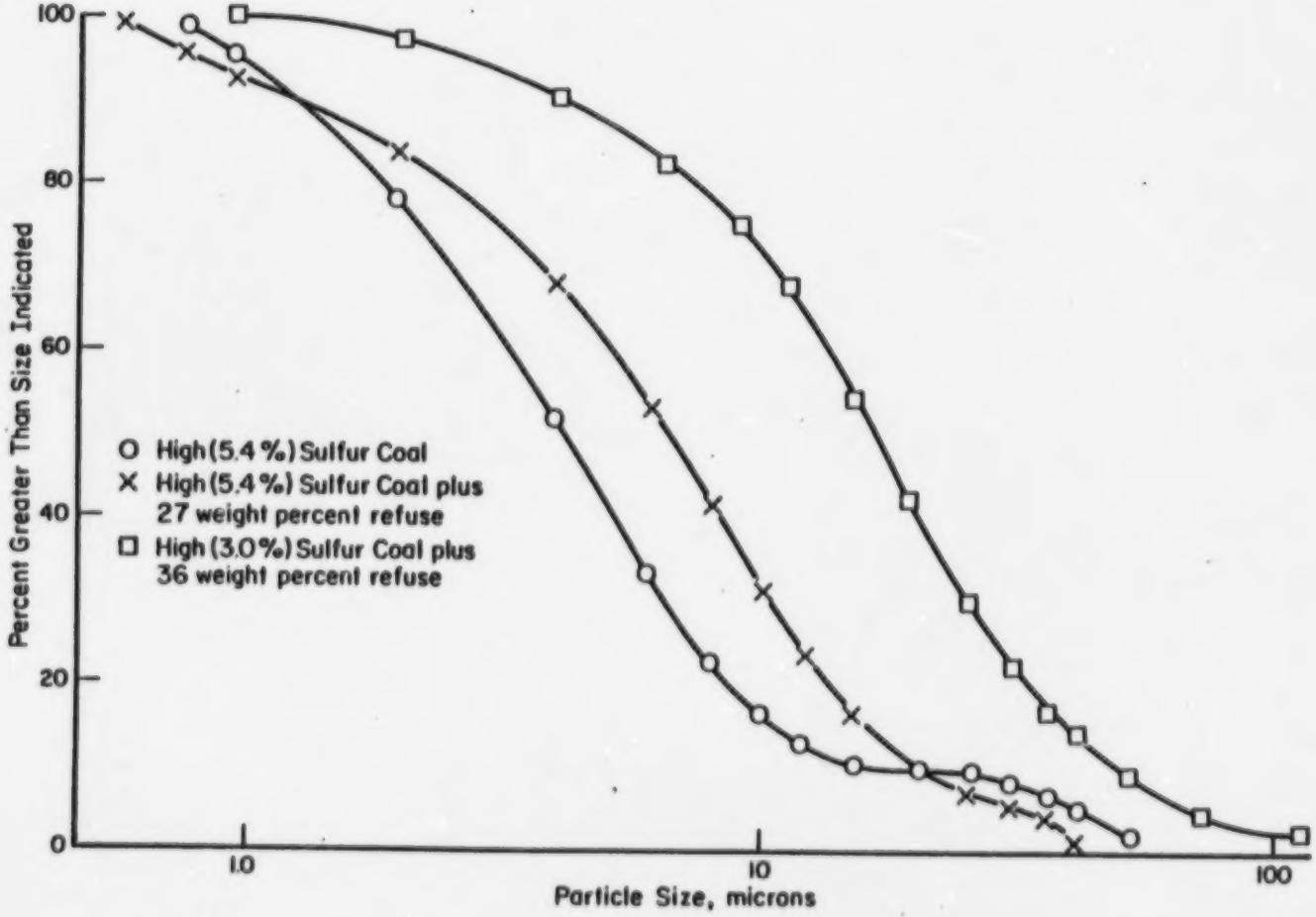

Figure 23. Particle size distribution of stack emission solids.

TABLE 13. PARTICULATE CONCENTRATIONS AT ECONOMIZER OUTLET

Run No.	Fuel	Steam flow, lb/hr	Particulates, lb/hr	Particulates, gr/scf
1	3% S coal	85,000	378	1.714
2	3% S coal + 60 wt% refuse	80,000	352	1.295
3	3% S coal + 60 wt% refuse	80,000	316	1.271
4	3% S coal	75,000	330	2.37
5	3% S coal + 53 wt% refuse	78,000	346	2.03
6	3% S coal + 52 wt% refuse	87,000	347	2.71

These results indicate that cofiring of shredded refuse and coal does not necessarily increase particulate concentrations, and combustion conditions may be the controlling factor.

Measurements of the polycyclic organic matter (POM) in the stack emissions resulted in a wide range of values and indicated that combustion conditions in the furnace are more important than the fuel in determining the POM output. The POM values obtained early in the program when coal alone was burned were much higher than that measured under good combustion conditions near the close of the program:

Year	Sulfur in Coal, percent	POM, ng/m³
1974	1	6040
1974	3.2	7070
1975	5.2	3715
1977	2.3	95

These POM values are small compared to those found in a Battelle investigation of a small commercial stoker-fired boiler.[3] In that work a bituminous coal containing 1.2 percent sulfur gave POM concentrations ranging from 260,000 ng/m³ at a low firing rate up to 8.8 million ng/m³ at a high firing rate.

Some moderately high POM values were found early in this program when the agricultural equipment blower was used to feed the refuse into the furnace and combustion conditions were not optimized. Low values were obtained when the air-swept spout system was used for refuse feeding at the close of the program:

[3]Giammar, R. D., Engdahl, R. B., and Barrett, R. E., Emissions from Residential and Small Commercial Stoker-Coal-Fired Boilers Under Smokeless Operation, EPA 600/7-76-029, October, 1976.

Feed System	Fuel Mixture	POM, ng/m³
Agricultural blower	3.2% S coal +42 wt % refuse	12,060
Agricultural blower	3.2% S coal +36 wt % refuse	22,940
Agricultural blower	5.2% S coal +27 wt % refuse	159,000
Air-swept spout	2.3% S coal +42 wt % refuse	140
Air-swept spout	2.3% S coal +42 wt % refuse	28

These results indicate that the refuse-feed system and its subsequent effect on combustion conditions may be the most important factor in the formation of the POM compounds. Under favorable conditions, the POM emissions from cofiring of refuse and coal can be less than those from coal alone.

SECTION 7

FURNACE RESIDUE STUDIES

ASH FUSION AND SLAGGING

On several occasions, with high delivery rates of refuse, deposits accumulated on the water walls. In some instances these deposits were heavy enough to fall from the overhanging tubes and to jam the hydraulically powered grate. Immediate corrective actions were taken to increase the overfire air velocity under the tubes hanging over the coal entry ports on the front wall of the boiler.

Also, the refuse distribution was broadened by slowing the frequency of air pulses divided between the two refuse feeders. This combination of better refuse distribution and additional air flow eliminated the heavy slagging on the tubes.

This slagging was also later associated with the coal, whose ash fusion temperature was the lowest in the measured range of 1200 to 1370 C (2200 to 2500 F). Furthermore, the fusion temperature of the bottom ash from combined fuels had an even lower value of 1160 C (2120 F). Thus, this batch of Ohio coal, along with the heavy refuse feed, contributed to easily melted ash. Although redistribution of air and trash eliminated the avalanching clinkers, the deposits continued to form on the bed of coals.

Subsequent spectrographic analysis showed a similarity of elements concentrated from the refuse into the bottom and fly ash as well as in the clinker taken from the water-wall tubes. The yellowish porous slag generated by burning refuse with coal showed a fourfold increase in zinc, with smaller increases in chromium, lead, sodium, calcium, and magnesium, when compared to the concentrations found in slag deposits formed with coal only.

Low fusion temperatures for the ash of combined fuels was also evidenced by a viscous layer on top of the burning solids on the moving grate. This cohesive layer tended to obscure the air flow. As a result, the bottom ash contained some unburnt fuel. In several instances the bottom ash contained combustible material equivalent to about 14 to 28 percent of the calorific value of the original coals. Close inspection of the bottom ash revealed chunks of coal but no evidence of uncharred refuse. Since the heavy coal particles were thrown toward the rear of the furnace, they were moved into the ash pit faster than any heavy refuse particle. As a result, the refuse was converted to slag and ashes more completely than the coal. Therefore the cofiring of refuse and coal produces lower melting ashes or deposits. As long as the location of ash deposits can be controlled, overall protection of the environment may be enhanced. That is, undesirable products may be concentrated in the ashes and the combustion efficiency boosted by improved air distribution.

FLY ASH AND GRATE ASH ANALYSES

The compositions of the grate ashes and filter catches obtained in the stack are shown in Tables 14 and 15. The results of the analyses showed that some of the sulfur remained in the grate ash. The amount in the ash was greater when refuse was burned with the coal. When a sample of typical grate ash was leached with water, the bulk of the water-soluble material was calcium sulfate. Since there is substantially more calcium in the refuse than in the coal, it appears that this sulfate has been formed primarily from reaction with the refuse component.

Another significant difference when refuse was burned with the coal was an increase in the sulfur content of the filter catch. This result is in agreement with the concept that particulate chlorides are converted to sulfates in the flue-gas stream by reaction with the SO_2 from the coal. Calcium, magnesium, and sodium also were present at higher concentrations in the filter catches from refuse-coal burning. In addition, many of the trace metals were concentrated in the filter catch from the combined fuel runs. The metals such as lead, zinc, and tin, which are present in greater amounts in refuse than in coal, showed the greatest increases in the filter catch.

TABLE 14 COMPOSITION OF PARTICULATES

Element	Concentration, weight percent														
	High-sulfur coal (5.2% S)	High-sulfur coal (3.3% S)			High-sulfur coal (2.4% S)		Low-sulfur coal (0.9% S)		27 wt % refuse + high-sulfur coal (5.2% S)	36 wt % refuse + high-sulfur coal (3.8% S)	38 wt % refuse + high-sulfur coal (2.4% S)	44 wt % refuse + high-sulfur coal (2.4% S)	52 wt % refuse + high-sulfur coal (2.4% S)	53 wt % refuse + high-sulfur coal (2.4% S)	60 wt % refuse + high-sulfur coal (2.4% S)
	Filter catch	Windbox ash	Fly ash	Filter catch	Fly ash	Cyclone catch	Fly ash	Filter catch	Filter catch	Filter catch	Fly ash	Cyclone catch	Cyclone catch	Cyclone catch	Fly ash
Nonmetals															
S	2.2	3.7	1.8	12.6	1.0	0.8	1.8	1.5	3.7	3.9	1.0	1.1	1.1	1.8	0.8
Cl	<0.1	<0.02	<0.02	0.04	Nil	0.01	0.6	0.75	<0.1	0.09	0.04	0.22	0.3	0.2	0.25
C	27.3	ND	ND	ND	ND	ND	ND	ND	26.7	27.8	ND	ND	ND	ND	ND
H	1.6	ND	ND	ND	ND	ND	ND	ND	1.5	1.7	ND	ND	ND	ND	ND
H_2O	Nil	ND	ND	ND	ND	ND	ND	ND	Nil	Nil	ND	ND	ND	ND	ND
Major metals															
Si	5–10	15	15	7.5	5–10	10–30	10	10	5–10	5–10	10–15	10–30	10–30	20–40	10–30
Fe	5–10	15	10	6	4–6	5–10	4.5	4.5	5–10	3–5	3–6	4–6	4–6	5–10	4–6
Al	2–4	7.5	7.5	3	4–6	5–10	5.5	7.5	2–4	2–4	4–6	5–10	5–10	5–10	5–10
Ca	0.3	3	7.5	1	0.5	0.8–2	1	1	1.0	2–4	2–4	3–6	3–6	5–10	1–5
Mg	0.1	0.3	0.3	0.2	0.2	0.6	0.3	0.3	0.3	0.4	0.4	0.8	0.6	0.8–2.0	0.8
Na	0.1	0.1	0.1	1	0.8	0.3	0.3	0.5	1.0	1.0	0.8	0.8–2.0	0.8–2.0	1–5	0.8–2.0
K	1.0	1	1	1	0.2	3–6	0.5	1	1.0	1.0	1–2	3–6	3–6	3–6	3–6
Ti	0.1	0.4	0.3	0.3	0.2	0.5	0.3	0.5	0.2	0.2	0.2	0.5	0.6	0.6	0.4
Toxic trace metals[a]															
Pb	0.03	<0.01	<0.01	0.3	0.01	0.3	0.01	0.1	0.3	0.3	0.03	0.06	0.08	0.1	0.06
As	<0.1	<0.1	<0.1	0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1
Cd	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1
Be	0.001	<0.001	<0.001	0.007	<0.001	<0.001	<0.003	<0.003	0.001	<0.0005	<0.001	<0.001	<0.001	<0.001	<0.001
Other trace metals															
Zn	0.05	<0.1	<0.1	0.3	<0.1	<0.1	<0.1	<0.1	0.3	1.0	<0.1	0.1	0.1	0.2	0.04
Sn	<0.002	<0.01	<0.01	0.02	<0.01	<0.1	<0.01	0.1	3.02	0.05	<0.01	<0.01	0.02	0.04	<0.01
Mn	0.005	0.03	0.06	0.02	0.01	0.02	0.01	0.01	0.03	0.04	0.03	0.05	0.05	0.05	0.04
Ba	0.02	0.03	0.05	0.02	0.01	0.05	0.1	0.06	0.04	0.03	0.02	0.06	0.06	0.08	0.04
B	0.05	0.03	0.02	0.2	0.03	0.05	0.04	0.06	0.08	0.1	0.02	0.05	0.05	0.05	0.05
V	0.01	0.02	0.01	0.03	<0.01	0.02	0.03	0.03	0.01	0.01	<0.01	0.02	0.02	0.02	0.01
Mo	0.002	<0.01	<0.01	0.02	<0.01	<0.01	<0.005	<0.005	0.005	0.01	<0.01	<0.01	<0.01	<0.01	<0.01
Cr	0.01	<0.01	<0.01	0.01	<0.01	0.02	0.01	0.03	0.02	0.02	<0.01	0.02	0.06	0.06	0.02
Zr	0.005	0.02	0.01	0.01	0.01	0.02	0.02	0.02	0.01	<0.01	0.02	0.02	0.05	0.02	0.02
Cu	0.01	0.005	0.003	0.1	0.01	0.03	0.03	0.2	0.02	0.02	0.01	0.03	0.03	0.03	0.04
Ni	0.01	<0.005	<0.005	0.03	< .01	0.04	<0.01	0.03	0.02	0.02	<0.01	<0.01	0.05	0.08	0.02
Co	0.005	<0.01	<0.01	0.01	<0.01	<0.01	<0.01	0.02	0.005	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01
Sr	0.03	0.05	0.01	0.01	0.01	0.03	0.06	0.06	0.03	0.03	0.02	0.03	0.03	0.04	0.02
H_2O soluble	ND	0.34	2.9	ND	ND	2.1	4.2	ND	ND	ND	ND	3.2	3.5	5.3	2.3

(a) Analytical technique not sensitive to Hg and Se.
ND = not determined.

TABLE 15 COMPOSITION OF GRATE ASH

Element	Concentration, weight percent										
	High-sulfur coal (5.2% S)	High-sulfur coal (3.3% S)	High-sulfur coal (2.4% S)	Low-sulfur coal (0.9% S)	27 wt % refuse + high-sulfur coal (5.2% S)	36 wt % refuse + high-sulfur coal (3.8% S)	38 wt % refuse + high-sulfur coal (2.4% S)	50 wt % refuse + high-sulfur coal (2.6% S)		52 wt % refuse + high-sulfur coal (2.4% S)	53 wt % refuse + high-sulfur coal (2.4% S)
								Separate feed	Combined feed		
Nonmetals											
S	1.0	0.1	0.9	0.4	1.7	1.9	4.9	2.15	1.74	1.1	0.7
Cl	0.003	<0.02	0.02	0.2	0.03	0.013	Nil	0.02	0.01	0.01	<0.01
C	27.8	ND	ND	ND	16.1	21.5	ND	ND	ND	ND	ND
H	0.67	ND	ND	ND	0.73	0.7	ND	ND	ND	ND	ND
H_2O	1.42	ND	ND	ND	0.71	1.43	ND	ND	ND	ND	ND
Major metals											
Si	5–10	15	10–15	10	5–10	10–20	10–15	15	15	10–15	10–15
Fe	15–25	1-5	5–12	4.5	15–25	8–12	8–12	15	15	4–6	5–10
Al	3–6	7.5	5–8	7.5	4–8	4–7	5–8	7.5	7.5	5–7	5–7
Ca	1.0	3	1	0.3	0.3	2–4	2–4	1	1	2–3	4–5
Mg	0.3	0.3	0.4	0.2	0.2	0.5	0.4	0.3	0.3	0.5	0.5
Na	1.0	0.1	0.1	0.2	0.3	1.0	0.8	1	1	0.5–1.0	0.5–1.0
K	1.0	1	2–3	1	1.0	1.0	1–2	2	2	2–3	1–2
Ti	0.2	0.3	0.2	0.5	0.2	0.2	0.2	0.5	0.5	0.2	0.2
Toxic trace metals(a)											
Pb	0.02	<0.01	<0.01	<0.01	0.003	0.01	0.01	0.003	0.005	0.01	0.01
As	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1
Cd	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1
Be	<0.0005	<0.001	<0.001	<0.003	0.0005	<0.0005	<0.001	0.001	0.002	<0.001	<0.001
Other trace metals											
Zn	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1
Sn	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01
Mn	0.01	0.03	0.01	0.005	0.01	0.03	0.02	0.03	0.03	0.03	0.03
Ba	0.06	0.05	0.05	0.03	0.2	0.05	0.02	0.04	0.04	0.03	0.03
B	0.02	0.02	0.03	<0.01	0.01	0.02	0.02	0.02	0.02	0.03	0.03
V	0.01	0.01	0.01	0.01	0.02	0.01	<0.01	0.01	0.01	0.01	0.01
Mo	0.003	<0.01	<0.005	<0.005	0.005	<0.01	<0.01	0.003	0.003	<0.005	<0.005
Cr	0.005	<0.01	0.01	0.01	0.005	0.01	<0.01	0.02	0.02	0.01	0.01
Zr	0.01	0.01	0.01	0.02	0.02	0.01	0.02	0.01	0.01	0.01	0.01
Cu	0.03	0.003	0.01	0.02	0.01	0.02	0.01	0.02	0.02	0.02	0.02
Ni	0.01	<0.005	<0.01	<0.01	0.02	<0.01	<0.01	0.007	0.01	<0.01	<0.01
Co	0.005	<0.01	<0.01	<0.01	0.01	<0.01	<0.01	0.005	0.005	<0.01	<0.01
Sr	0.03	0.03	0.03	0.03	0.06	0.02	0.02	0.02	0.02	0.03	0.03
H_2O soluble	0.73	0.92	ND	0.68	0.19	0.23	ND	0.78	0.69	ND	ND

(a) Analytical technique not sensitive to Hg and Se.
ND = not determined.

APPENDIX A

PROBE SPECIMEN DATA

TABLE A-1 ACTUAL WEIGHT LOSSES AND EQUIVALENT TUBE WASTAGES PLUS METAL TEMPERATURES IN COLUMBUS PROBES

	Probe 27 (8 Hr)			Probe 28 (8 Hr)			Probe 29 (8 Hr)		
	Loss		Avg metal	Loss		Avg metal	Loss		Avg metal
Specimen	Grams	Mils	temp, F	Grams	Mils	temp, F	Grams	Mils	temp, F
A106-1	.1835	.241	484	.0637	.0834	645	.0072	.0094	402
T11-2	.1460	.192	500	.0435	.0569	665	.0108	.0142	440
310-3	.0000	.0	512	.0001	.0001	685	.0004	.0005	470
JS700-4	.0000	.0	528	.0000	.0000	705	.0001	.0001	500
446-5	.0010	.0013	540	.0010	.0013	725	.0021	.0027	530
316-6	.0013	.0017	555	.0028	.0037	745	.0006	.00079	560
A106-7	.1236	.162	568	.0630	.0825	765	.0277	.0363	590
T11-8	.0681	.089	580	.0750	.0983	785	.0137	.0179	610
310-9	.0010	.013	598	.0019	.0025	808	.0003	.00039	638
JS700-10	.0010	.013	615	.0019	.0025	825	.0002	.00026	660
446-11	.0042	.006	635	.0022	.0029	845	.0105	.0137	680
316-12	.0020	.003	658	.0085	.0111	860	.0008	.00104	700
A106-13	–	–	678	.1460	.1913	880	.0726	.0951	715
T11-14	.0652	.085	700	–	–	900	.0437	.0572	735
310-15	.0004	.0005	730	.0022	.0030	918	.0000	.0000	755
JS700-16	.0013	.0017	760	.0015	.0019	937	.0007	.00092	775
446-17	.0217	.028	800	.0030	.0039	955	.0032	.0042	795
316-18	.0048	.006	839	.0096	.0126	975	.0030	.0039	814

	Probe 30 (8 Hr)			Probe 31 (8 Hr)			Probe 32 (2.5 Hr)		
	Loss		Avg metal	Loss		Avg metal	Loss		Avg metal
Specimen	Grams	Mils	temp, F	Grams	Mils	temp, F	Grams	Mils	temp, F
A106-1	.0270	.0354	582	.0156	.02044	514	.0594	.0778	710
T11-2	.0322	.0422	605	.0238	.03118	550	.0445	.0583	725
310-3	.0000	.0000	630	.0016	.00209	585	.0020	.0026	740
JS700-4	.0004	.00052	655	.0027	.00354	615	.0036	.0047	750
446-5	.0045	.00589	680	.0062	.00812	650	.0051	.0067	765
316-6	.0037	.00485	705	.0057	.00747	680	.0027	.0035	780
A106-7	.0645	.08449	735	.0592	.07755	710	.0663	.0868	790
T11-8	.0340	.04454	760	.0412	.05397	740	.0367	.0481	800
310-9	.0002	.00026	787	.0039	.00511	763	.0010	.0013	815
JS700-10	.0005	.00065	805	.0036	.00472	800	.0030	.0039	825
446-11	.0048	.00629	825	.0058	.00759	820	.0059	.0077	835
316-12	.0049	.00642	840	.0071	.00930	840	.0052	.0068	845
A106-13	.1202	.15746	860	.1557	.20397	860	.1027	.1345	855
T11-14	.0721	.09445	875	.1218	.15956	885	.0849	.1112	865
310-15	.0047	.00616	895	.0055	.00721	905	.0037	.0048	875
JS700-16	.0014	.00183	915	.0040	.00524	925	.0040	.0052	885
446-17	.0124	.01624	930	.0065	.00852	940	.0036	.0047	895
316-18	.0040	.00524	962	.0039	.00511	964	.0072	.0094	910

TABLE A-1 (Continued)

Specimen	Probe 33 (8 Hr) Loss Grams	Loss Mils	Avg metal temp, F	Probe 34 (8 Hr) Loss Grams	Loss Mils	Avg metal temp, F
A106-1	.0330	.0432	624	.0231	.0303	553
T11-2	.0432	.0566	630	.0236	.0309	568
310-3	.0049	.0064	634	.0005	.0006	580
405-4	.0351	.0459	642	.0137	.0179	592
446-5	.0070	.0092	647	.0020	.0026	607
316-6	.0023	.0030	652	.0013	.0017	620
A106-7	.0793	.1039	660	.0646	.0846	635
T11-8	–	–	667	.0718	.0941	650
310-9	.0020	.0026	680	.0016	.0021	663
405-10	.0508	.0665	687	.0186	.0244	685
446-11	.0021	.0028	702	.0020	.0026	705
316-12	.0177	.0232	717	.0112	.0147	730
A106-13	.1996	.2615	737	.1954	.2559	760
T11-14	.1869	.2448	762	.1356	.1776	793
310-15	.0053	.0069	792	.0028	.0037	830
405-16	.0607	.0796	822	.0171	.0224	870
446-17	–	–	862	.0018	.0024	920
316-18	.0039	.0052	913	.0068	.0089	983

Specimen	Probe 35 (8 Hr) Loss Grams	Loss Mils	Avg metal temp, F	Probe 36 (8 Hr) Loss Grams	Loss Mils	Avg metal temp, F
A106-1	.0272	.0356	618	.0175	.0229	632
T11-2	.0181	.0237	640	.0254	.0333	650
310-3	.0000	.0000	655	.0006	.0008	668
405-4	.0015	.0019	675	.0290	.0380	685
446-5	.0473	.0619	690	.0775	.1015	705
316-6	.0035	.0046	710	.0025	.0033	720
A106-7	.0663	.0868	725	.1120	.1467	740
T11-8	.0519	.0679	740	.0489	.0641	758
310-9	.0003	.0004	757	.0012	.0016	774
405-10	.0387	.0507	775	.0807	.1057	795
446-11	.0952	.1247	790	.0808	.1058	815
316-12	.0203	.0266	810	.0132	.0173	835
A106-13	.1358	.1779	825	.1839	.2409	850
T11-14	.0915	.1199	840	.0998	.1307	870
310-15	.0020	.0026	855	.0051	.0067	890
405-16	.0553	.0724	875	.0611	.0800	910
446-17	.1170	.1533	890	.0804	.1053	928
316-18	.0270	.0354	903	.0130	.0170	946

TABLE A-1 (Continued)

Specimen	Probe 37 (8 Hr) Loss Grams	Loss Mils	Avg metal temp, F	Probe 38 (708 Hr) Loss Grams	Loss Mils	Avg metal temp, F
A106-1	.0283	.0373	492	1.4076	1.855	492
ALP5-2*	–	–	546	.2777	–	530
310-3	.0036	.0047	601	.0306	.0394	565
P9-4	.0881	.1154	652	.5427	.7099	599
347-5	.0149	.0195	702	.1222	.1576	630
316-6	.0248	.0320	743	.1772	.2286	660
A106-7	.1235	.1627	781	1.1884	1.566	689
ALP5-8*	–	–	814	.2729	–	716
310-9	.0067	.0087	843	.0160	.0206	742
P9-10	.0754	.0987	867	.5570	.7286	764
347-11	.0155	.0203	886	.2531	.3265	787
316-12	.0280	.0366	905	.4199	.5417	805
A106-13	.1158	.1516	920	2.1295	2.807	824
ALP5-14*	–	–	934	–	–	841
310-15	.0062	.0081	946	.0745	.0961	857
P9-16	.0691	.0905	958	.6907	.9035	872
347-17	.0113	.0148	970	.4017	.5182	885
316-18	.0217	.0284	982	.3850	.4967	896

Specimen	Probe 39 (79 Hr) Loss Grams	Loss Mils	Avg metal temp, F	Probe 40 (75 Hr) Loss Grams	Loss Mils	Avg metal temp, F
A106-1	.1572	.207	590	.4841	.638	405
ALP5-2*	–	–	603	–	–	500
310-3	.0041	.005	620	.0030	.00386	563
P9-4	.1270	.1665	637	.2492	.327	606
347-5	.0289	.0372	655	.0158	.02035	643
316-6	.0506	.0652	675	.0181	.0233	671
A106-7	.2178	.2871	694	1.0006	1.319	696
ALP5-8*	–	–	715	–	–	716
310-9	.0048	.00617	736	.0041	.00527	736
P9-10	.0830	.1088	760	.2622	.3437	751
347-11	.0345	.0444	783	.0140	.0180	768
316-12	.1014	.1304	807	.0006	.000773	783
A106-13	.6117	.8049	832	.2111	.278	797
ALP5-14*	–	–	857	–	–	811
310-15	.0122	.0157	881	.0114	.0147	824
P9-16	.2886	.3784	907	.0945	.124	835
347-17	.0690	.0888	930	.0152	.0196	848
316-18	.0723	.0930	955	.0100	.0129	860

*Alonized coatings afforded protection by intermetallic compounds of varying densities, hence uncertain thicknesses or weights.